SD 69-419-2

Study of ONE-MAN LUNAR FLYING VECHICLE
FINAL REPORT

Volume II
Mission Analysis

Space Division
North American Rockwell

SD 69-419-2

STUDY OF ONE-MAN LUNAR FLYING VEHICLE
FINAL REPORT

VOLUME II
MISSION ANALYSIS

Contract NAS9-9045

31 August 1969

FOREWORD

This volume presents the mission analysis results for the lunar flying vehicles study. This work was accomplished under the One-Man Lunar Flying Vehicle Contract (NAS9-9045), conducted by the North American Rockwell Space Division for the National Aeronautics and Space Administration Manned Spacecraft Center, Houston, Texas. Other Volumes of this report are:

- Volume 1. Summary
- Volume 3. Subsystem Studies
- Volume 4. Configuration Design
- Volume 5. Preliminary Design and Specification
- Volume 6. Training and Resources Plans

CONTENTS

Page

ILLUSTRATIONS

TABLES

TECHNICAL REPORT INDEX/ABSTRACT

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DESCRIPTIVE TERMS

*ONE-MAN LUNAR FLYING VEHICLE, *CONTROL SYSTEMS, *PROPULSION SYSTEMS, *TRAJECTORIES, *DESIGN, *TRAINING, *RESOURCES, *MISSION ANALYSIS

ABSTRACT

THE PRIMARY OBJECTIVES OF THIS STUDY WERE TO OPTIMIZE THE DESIGN AND TO DEVELOP SYSTEM SPECIFICATIONS OF THE LUNAR FLYING VEHICLE. THE SCOPE ENCOMPASSED PARAMETRIC INVESTIGATIONS, CONCEPT GENERATION, AND EVALUATION EFFORT FOR THE DEFINITION OF A RECOMMENDED CONCEPT; PRODUCTION OF A PRELIMINARY DESIGN AND DEVELOPMENT OF SYSTEMS SPECIFICATIONS OF THE RECOMMENDED CONCEPT; AND DEFINITION OF RESOURCES AND CREW TRAINING PLANS. IN ADDITION TO GENERATION OF THE LFV DESIGN, THE SCOPE OF THE STUDY INCLUDED LUNAR MODULE INTEGRATION, FLIGHT SUIT INTERFACE STUDIES, AND DEFINITION OF GROUND SUPPORT EQUIPMENT FOR EARTH AND LUNAR OPERATIONS.

AS A RESULT OF PARAMETRIC STUDIES CONDUCTED DURING THE FIRST PHASE OF THIS EFFORT, A CONCEPT WAS SELECTED WHICH HAS THE FOLLOWING CHARACTERISTICS: (1) STABILITY-AUGMENTED CONTROL, (2) FOUR GIMBALED ENGINES WHICH ARE CLUSTERED BENEATH THE VEHICLE, (3) A SEATED PILOT POSITION, AND (4) AN INTEGRAL X-FRAME LANDING GEAR WITH 6 HYDRAULIC ATTENUATORS. THIS VEHICLE IS CAPABLE OF CARRYING A 370-LB PAYLOAD IN ADDITION TO THE PILOT. THE DRY WEIGHT OF THE VEHICLE IS 304 LB. WHEN LOADED WITH 300 POUNDS OF LM DESCENT STAGE PROPELLANTS, THE VEHICLE CAN OPERATE WITH A 4.6 NAUTICAL MILE RADIUS WITH NO PAYLOAD.

INTRODUCTION

The mission analysis effort during the study focused on the investigation of problem areas associated with the successful use of the lunar flying vehicle (LFV) in the lunar environment. The term "successful" was interpreted as: providing at least the minimum mobility desired by the scientists,[1] being within the capability of the astronauts to assemble and operate, and being safely operational within the unique environment. Consequently, an analysis of lunar operations associated with the use of the LFV was performed as well as a comprehensive theoretical analysis of the flight performance of an LFV. Because of the uncertainty of the final design, the flight performance analysis was accomplished parametrically. In order to ascertain the feasibility of LFV operations during relatively brief lunar stay times, detailed time lines were generated for several types of mission conditions. Since one of the major areas of uncertainty and sources of potential hazard involved the effect of the LFV exhaust plume on the lunar soil, analyses of theoretical and experimental soil erosion data were conducted. The results of these analyses were reflected in the LFV operations and design. Finally, to lay the groundwork for the next phase and to assure the consideration of peripheral requirements that could bear on the detailed design of the LFV, an analysis of the GSE and LSE requirements was conducted. The analyses conducted in each of the above-mentioned areas are covered by a separate section within this volume.

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[1] NASA SP-157 - 1967 Summer Study of Lunar Science and Exploration (July 31-August 13, 1967. "It is expected that the lunar flying unit (LFU) will provide a mobility radius of 5 to 10 kilometers, which is a considerable improvement over the present capability, but not nearly enough" - Page 9, Summary and Recommendations. On page 63, Table V of the Geology Group Report stipulates an LFV range of 12 kilometers radius. Ten kilometers is equal to 5.4 n mi; 12 kilometers is equal to 6.5 n mi.

VEHICLE PERFORMANCE DATA

The objective of this task was to develop parametric performance data to assess the influence of the pertinent flight performance parameters on ranging capability of the LFV. The approach employed in developing these data was to first establish parametric data that indicates the regions of optimum performance for modified ballistic and constant-altitude trajectories. These data were obtained from closed-form solutions of the simplified equations of motion. A computer program was then used to obtain additional performance data on a more specific basis. This program relaxed many of the assumptions necessary in the closed-form analysis, but did not result in significantly different performance capability.

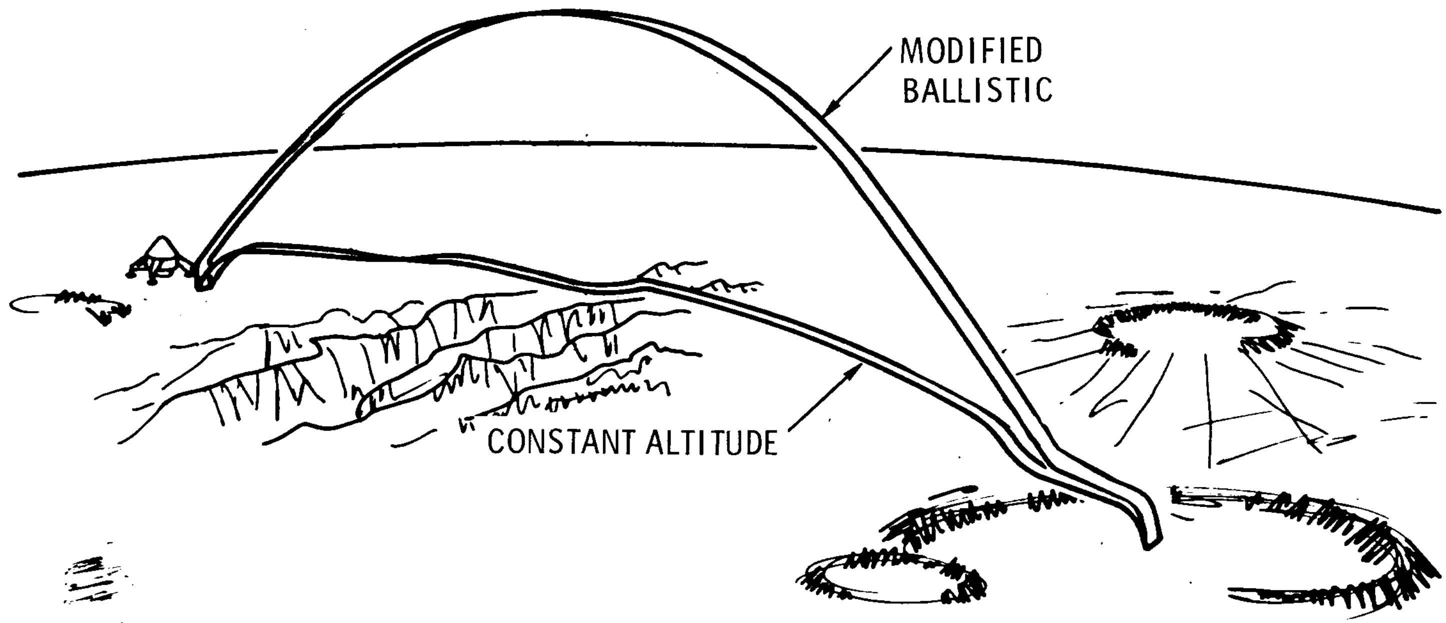
Data obtained from a Company-sponsored visual simulation (Reference 1) were utilized to determine pilot influence on vehicle performance, including instrumentation. These data were then used to develop the final performance characteristics of the vehicle concept recommended at the midterm point of the study. The results of these analyses are summarized in the following sections.

CLOSED-FORM SOLUTIONS

Closed-form solutions were obtained for the constant-altitude and modified ballistic trajectories and were utilized to obtain basic trajectory tradeoff data. The assumptions employed to derive these equations (contained in the Appendix) are:

1. Flat moon
2. Constant lunar gravity
3. Constant thrust-to-weight during segments of the trajectory
4. Constant specific impulse
5. Instantaneous pitch maneuvers between trajectory segments

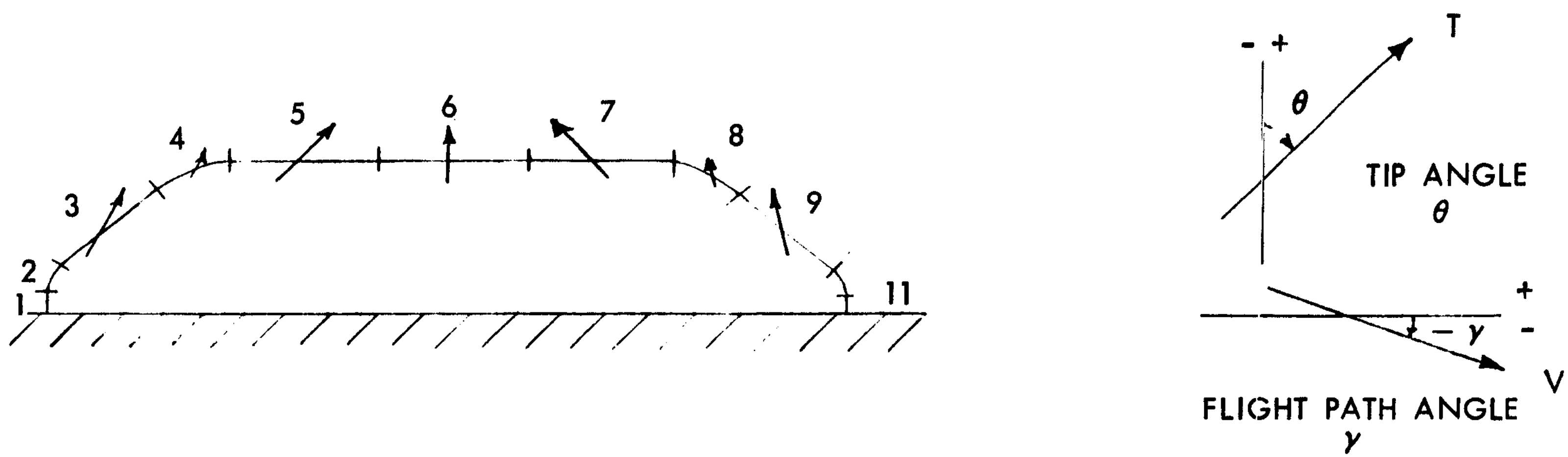
The purpose of this study was to determine the regions of optimality and the relative flight performance sensitivity near this region. Illustrations and segment descriptions for these two types of trajectories are shown in Figures 1 and 2 respectively.



SELECTION CRITERIA
PROPELLANT REQUIRED
PILOT DEMANDS
TARGET VISIBILITY

Figure 1. Alternative Flight Profiles

SEGMENT	DESCRIPTION	SEGMENT	DESCRIPTION
1	TAKEOFF HOVER, T/W = 1, θ = °, $\gamma = 90°$	7*	DECELERATE TO VELOCITY AT END OF SEGMENT 4
2	PITCH OVER TO DESIRED BOOST θ	8	THROTTLE TO LOW T/W AND DESCEND
3	BOOST	9	DEBOOST
4	THROTTLE TO LOW T/W AND COAST TO $\gamma = 0°$	10	PITCH TO $\theta = 0°$
5*	ACCELERATE TO OPTIMUM CRUISE VELOCITY, $\gamma = 0°$	11	HOVER AND LAND
6*	CRUISE AT OPTIMUM VELOCITY, $\gamma = 0°$, $\theta = 0°$, T/W = 1		



*REMOVING SEGMENTS 5 THROUGH 7 TRANSFORMS PROFILE TO MODIFIED BALLISTIC

Figure 2. Constant-Altitude Trajectory, Segment Description

Modified Ballistic Trajectory

The modified ballistic trajectory comprises four segments which result in a symmetrical trajectory about the midrange point. During the first segment, the boost phase, a high thrust to weight ratio (T/W) is applied at a constant vehicle pitch attitude (θ) for a given period of time. During the second segment, the ascent coast phase, T/W is reduced to a low constant value and the pitch angle may be different from that employed during the boost phase. During the last two segments, the descent coast phase and the deboost phase, the T/W is the same as for the ascent coast phase and the boost phase, respectively. The vehicle pitch attitudes relative to the horizontal are equal to $-\theta_1$ for the deboost phase and $-\theta_2$ for the descent coast phase.

In deriving the equations for the modified ballistic and constant-altitude modes, it was found that a normalized characteristic velocity parameter was obtained and could be used to assess regions of minimum ΔV independent of range. Additionally, it was found that reasonable values of minimum T/W and θ during the coast phases did not significantly affect ΔV. Figure 3 illustrates the major tradeoffs for the modified ballistic trajectory. The vehicle attitude during boost and ascent coast and during descent coast and deboost are assumed to be the same values. Figure 3a defines the normalized ΔV as a function of thrust attitude with respect to the vertical and boost and coast-phase T/W. The minimum normalized ΔV corresponds to a thrust vector attitude from the vertical of between 40 degrees and 50 degrees for all the T/W's in the region of interest. Figure 3b indicates that for a given throttle ratio, there is an optimum boost T/W. The modified ballistic trajectory is most efficient at high throttle ratio, asymtotically approaching an impulsively boosted ballistic trajectory.

Figures 4 and 5 show the maximum altitude and the velocity at maximum altitude, respectively, as a function of range and boost T/W for optimum boost angle modified ballistic trajectories. For the long-range trajectories, the maximum altitudes are quite high, reaching 6,300 feet for an 8 n mi range for a boost T/W of 2.0.

Constant Altitude Trajectory

Initial constant altitude trajectory data were obtained for a zero altitude. A typical trajectory is then comprised of a boost phase at a given pitch angle, a cruise phase at a zero pitch angle, and a deboost phase at a negative value of the boost phase pitch angle. The trajectory is symmetrical about the midrange point and the vertical component of thrust always results in $(T/W)_V = 1$.

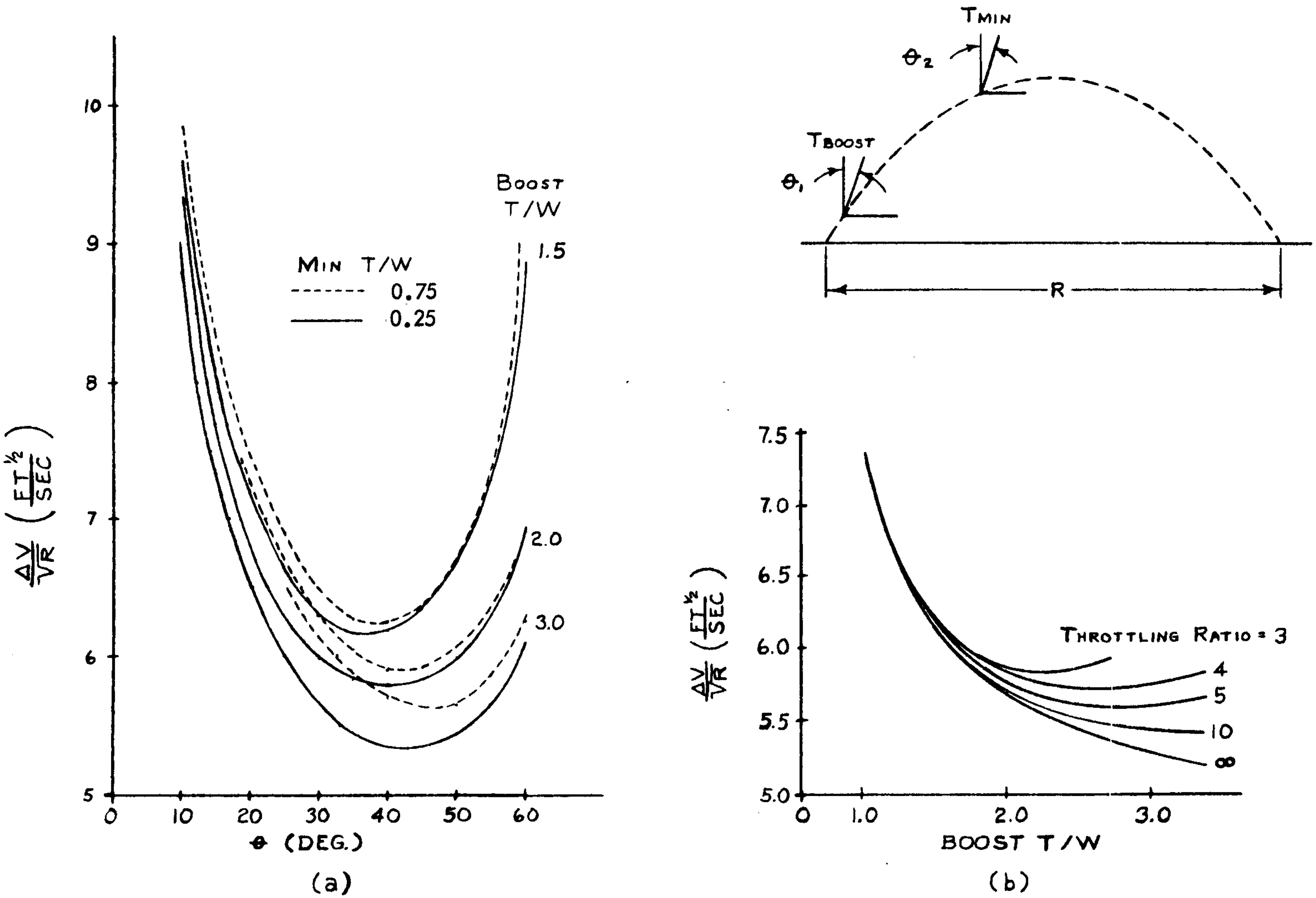


Figure 3 . Modified-Ballistic Mode Tradeoffs

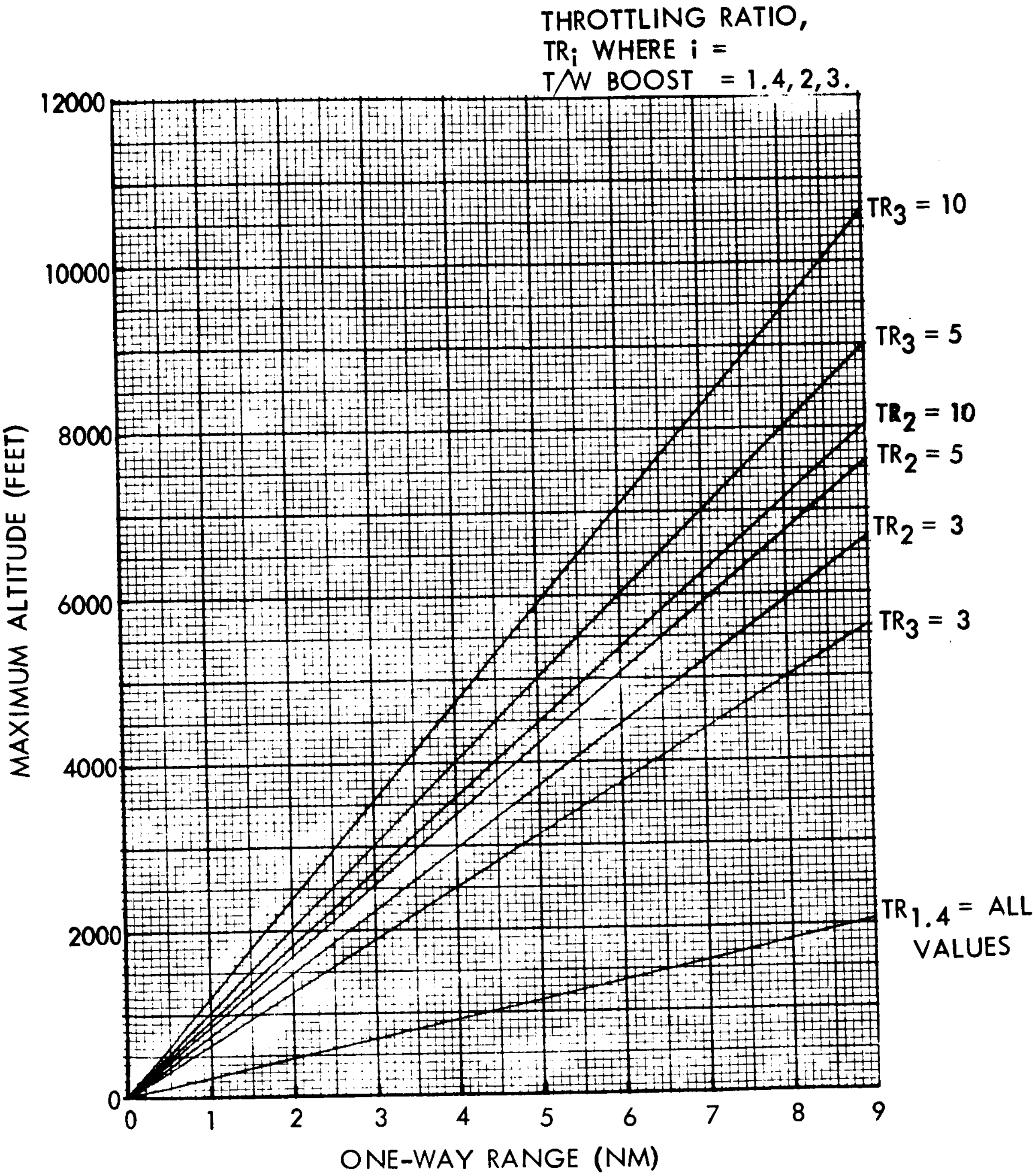


Figure 4. Modified-Ballistic Trajectory, Maximum Altitude

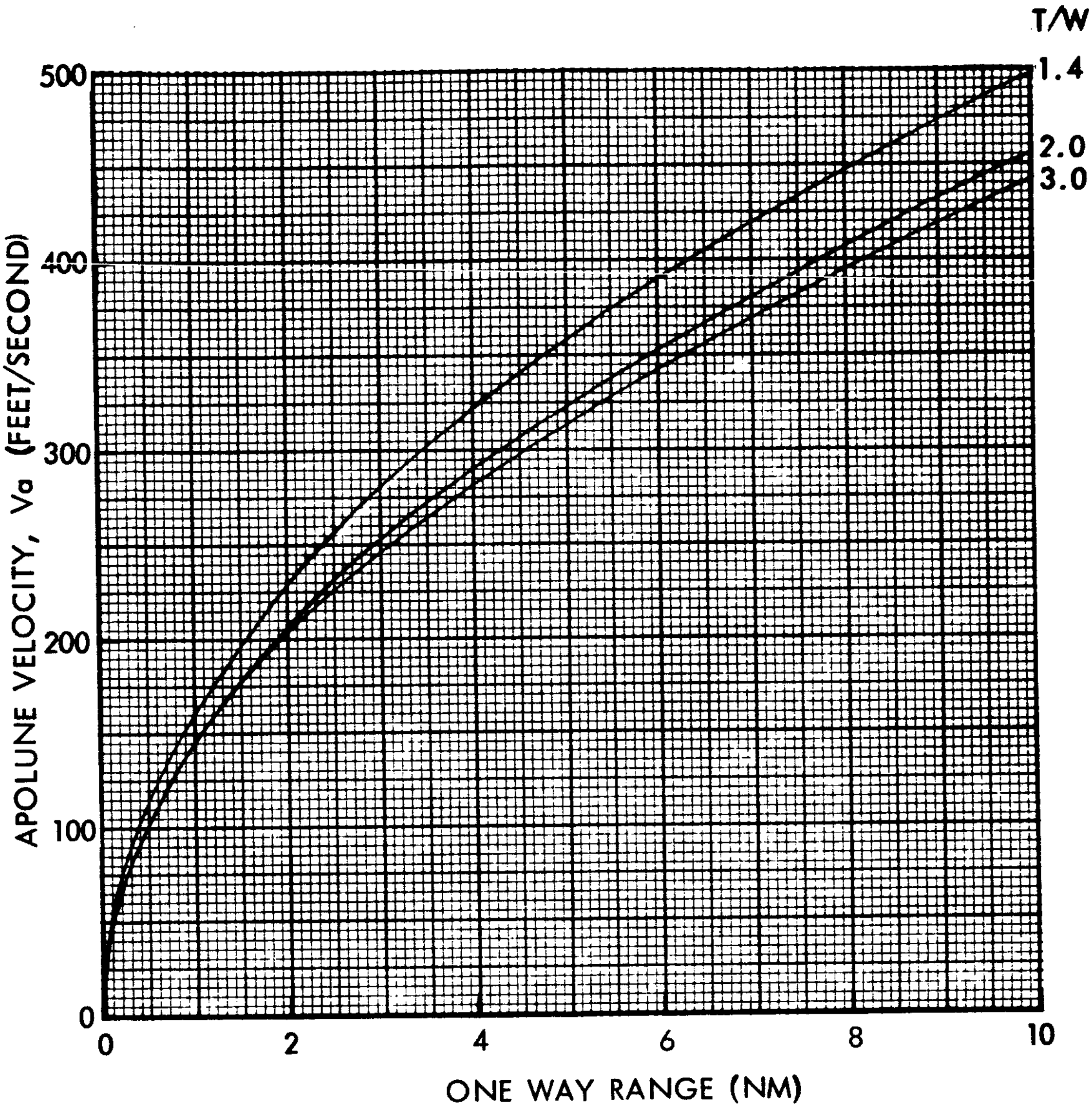


Figure 5. Modified-Ballistic Trajectory, Throttling Ratio = 5

The two parameters that affect performance efficiency are the boost pitch angle, θ , and the cruise velocity, V_c. Equations relating these parameters to the normalized characteristic velocity, $\Delta V/\sqrt{R}$, are given in the Appendix. These relationships are shown in Figures 6 and 7. Figure 6 shows the normalized optimum cruise velocity, $V_c/\sqrt{R}$, as a function of boost pitch angle, θ . Figure 7 gives the normalized characteristic velocity as a function of pitch angle for optimized V_c. The optimum pitch angle is 60 degrees from the vertical, but $\Delta V/\sqrt{R}$ is not significantly affected for boost pitch angles beyond 40 to 45 degrees. Human factor considerations would imply that the pitch angle be maintained at as low a value as possible while still being near the optimized performance region. For this reason, a pitch angle of 45 degrees was selected for further studies.

The effect of flying at non-optimum cruise velocities is shown in Figure 8. As the velocity is reduced to velocities significantly different from optimum, the propellant requirements increase rapidly. For example, optimum cruise velocity for a one-way range of 8 n mi is 375 ft/sec and the percentage of propellant to initial weight required is 14. 5. If the cruise velocity for this range is reduced to 100 ft/sec, this ratio is 26. 7 percent. If the percent of propellant is kept constant and the cruise velocity is reduced from optimum to 100 ft/sec, the range is reduced from 8 n mi to slightly less than 4 n mi.

For actual flights, the pilot will fly the constant-altitude trajectory at an altitude greater than zero. The desired altitude will depend upon several factors, including the minimum altitude for safe operation in case of a system malfunction, variations in the lunar surface altitude between the takeoff and landing site, and the range to be flown. Of the many ways of obtaining the desired altitude, two appear to essentially bound the problem. These are (1) a vertical ascent to altitude and (2) an optimum modified ballistic ascent. Of the two, it is obvious that the optimized modified ballistic mode is most efficient since the vertical ascent is a non-optimum end-point type of the modified ballistic trajectory. The effect of altitude on the normalized characteristic velocity for an 8 n mi trajectory is shown in Figure 9 as a function of the boost T/W during the ascent phase (a 45-degree boost-out to the optimum cruise velocity was assumed during the constant-altitude portion of the trajectory). This figure shows that there is no effect on $\Delta V/\sqrt{R}$ for T/W Boost = 1. 5 and that less than a 10 percent decrease in ΔV occurs going from 0 to 6, 000 feet for a T/W of 2. 0. It may be concluded that the altitude at which the constant-altitude flight occurs does not seriously affect propellant requirements if a modified ballistic trajectory is used to attain altitude and to descend. As shown in Figure 10, the increase in $\Delta V/\sqrt{R}$ can be appreciable at high altitudes if a vertical ascent is employed.

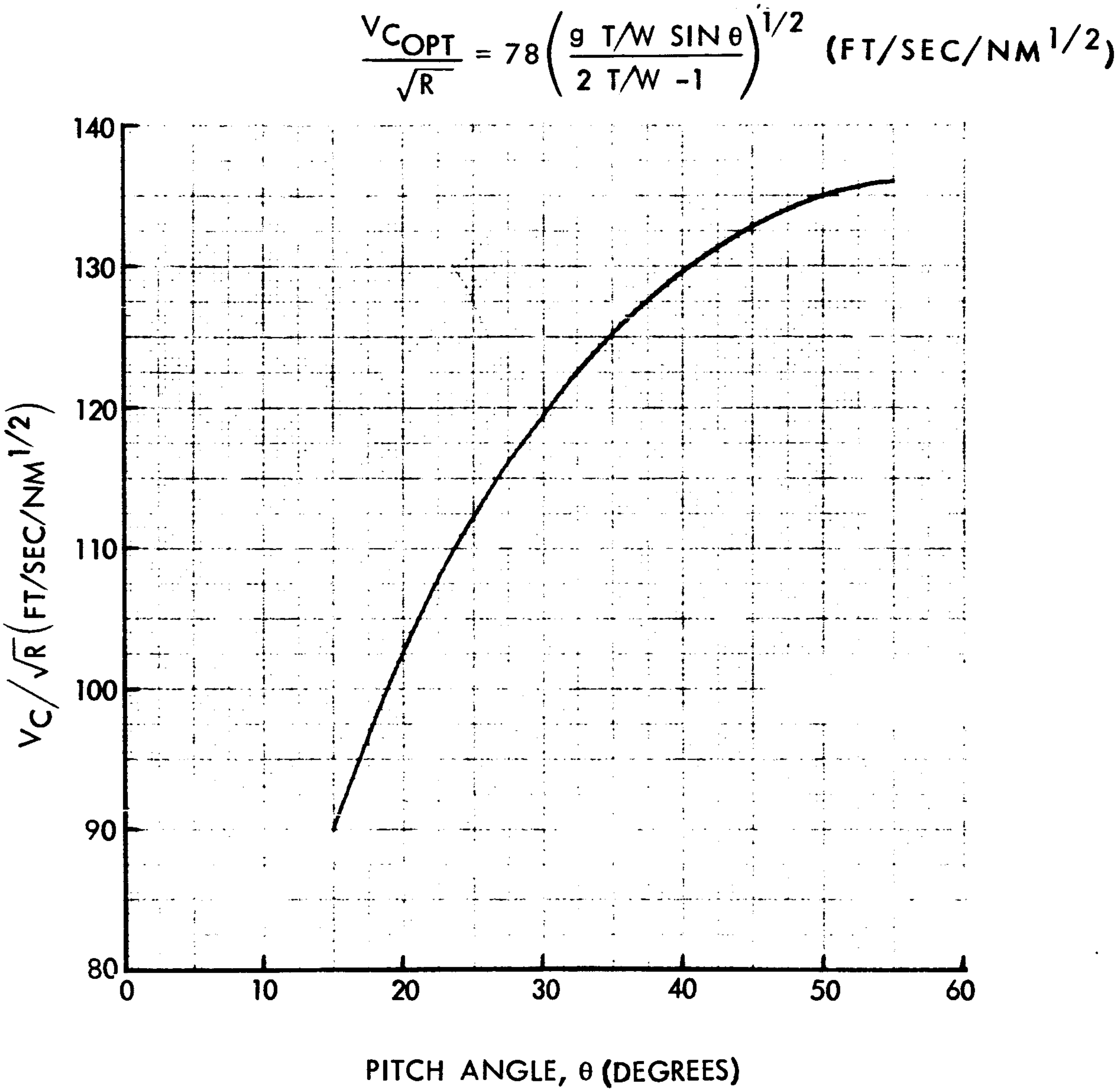


Figure 6. Normalized Optimum Cruise Velocity for Constant-Altitude Trajectories

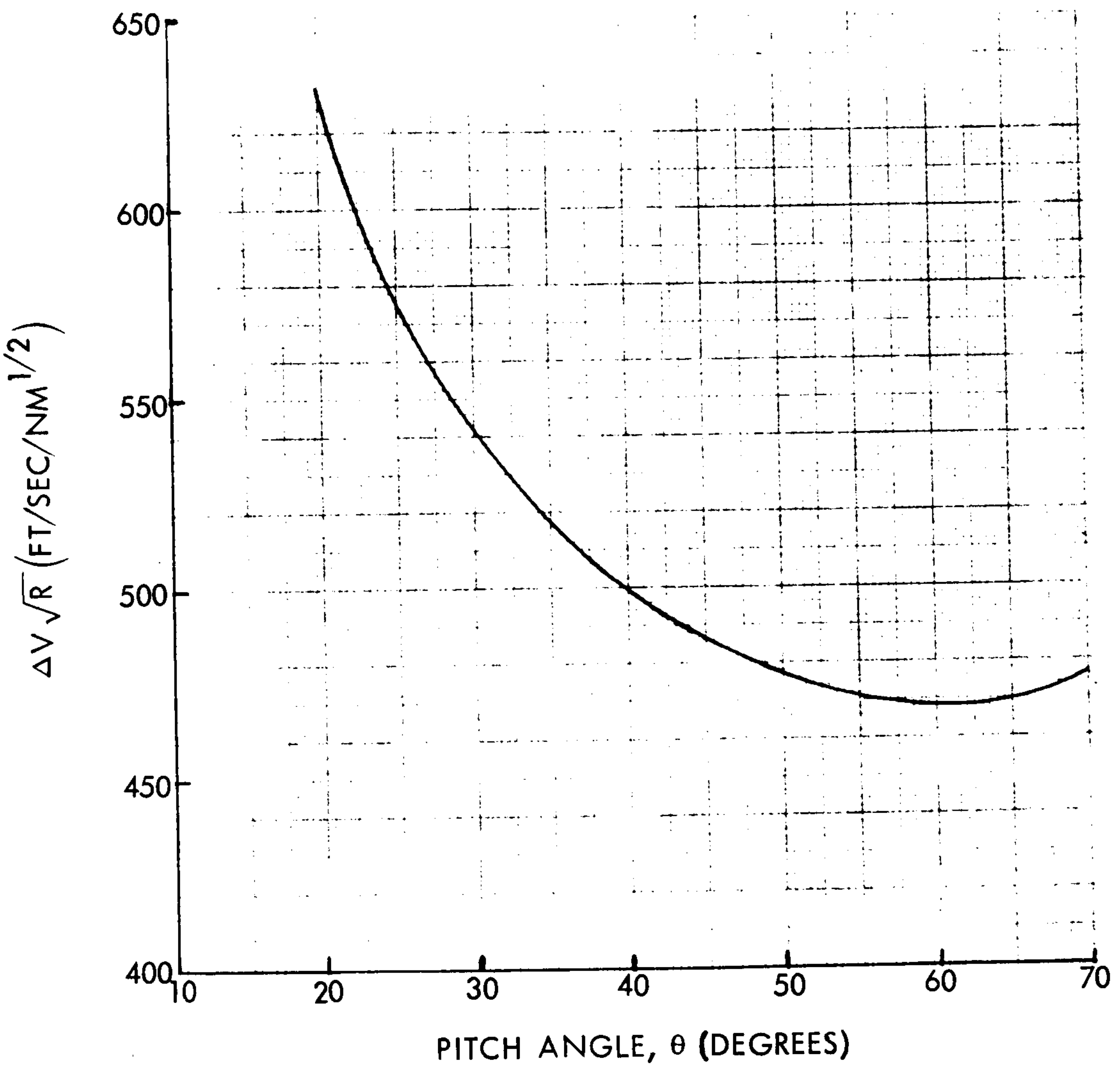


Figure 7. Normalized Characteristic Velocity With Optimum Cruise Velocity for Constant-Altitude Trajectories

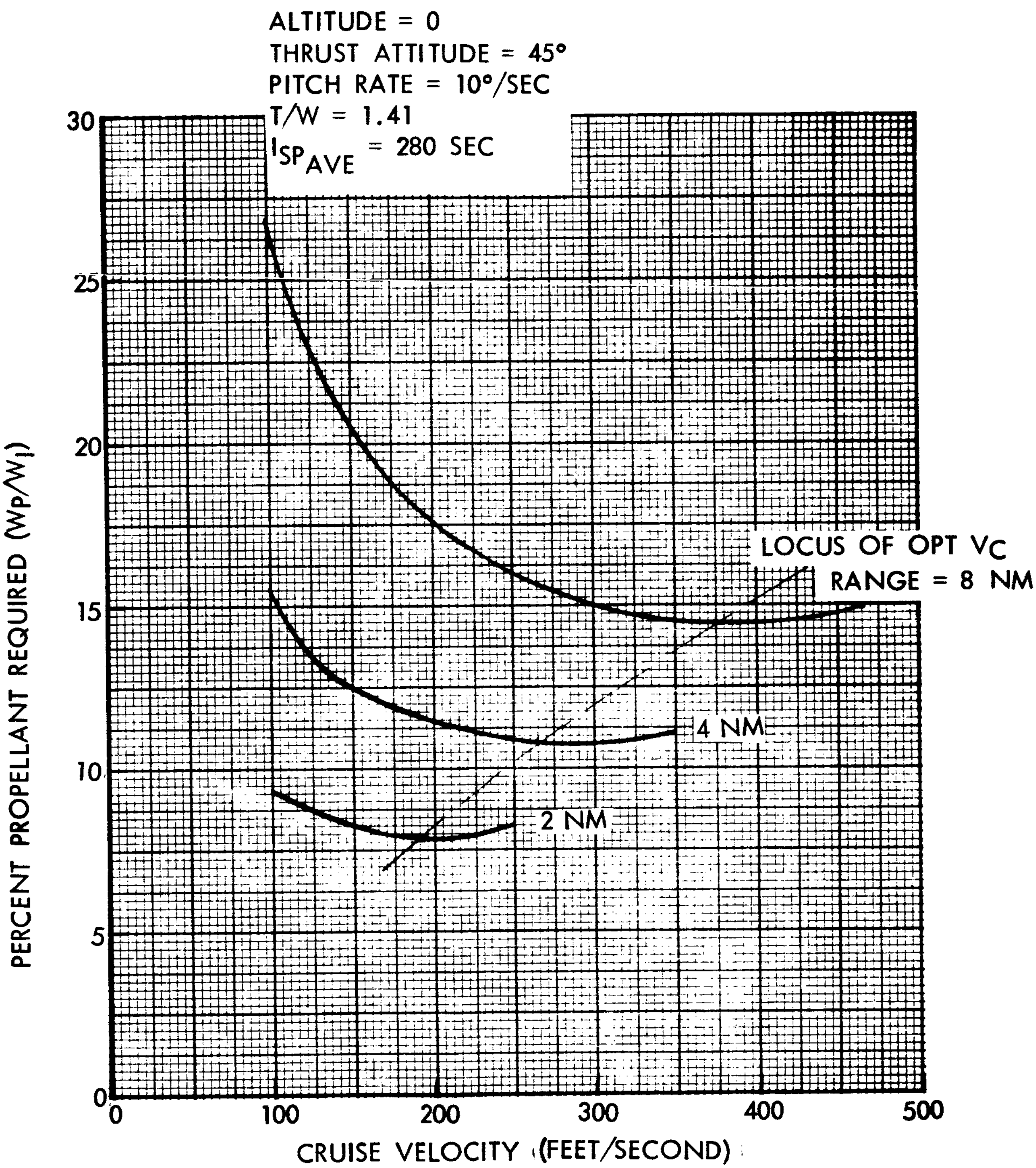


Figure 8. Constant-Altitude Trajectory, Effect of Cruise Velocity on Propellant Requirements

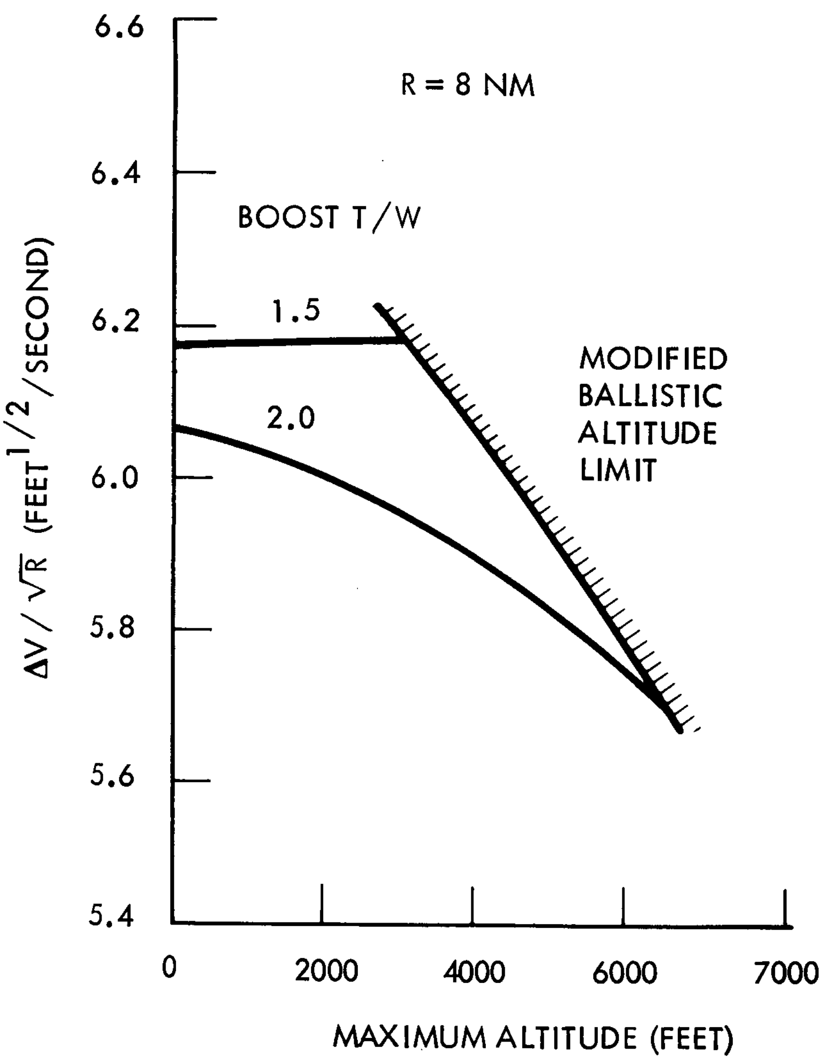


Figure 9. Effect of Altitude on Normalized Characteristic Velocity for Constant-Altitude Trajectory

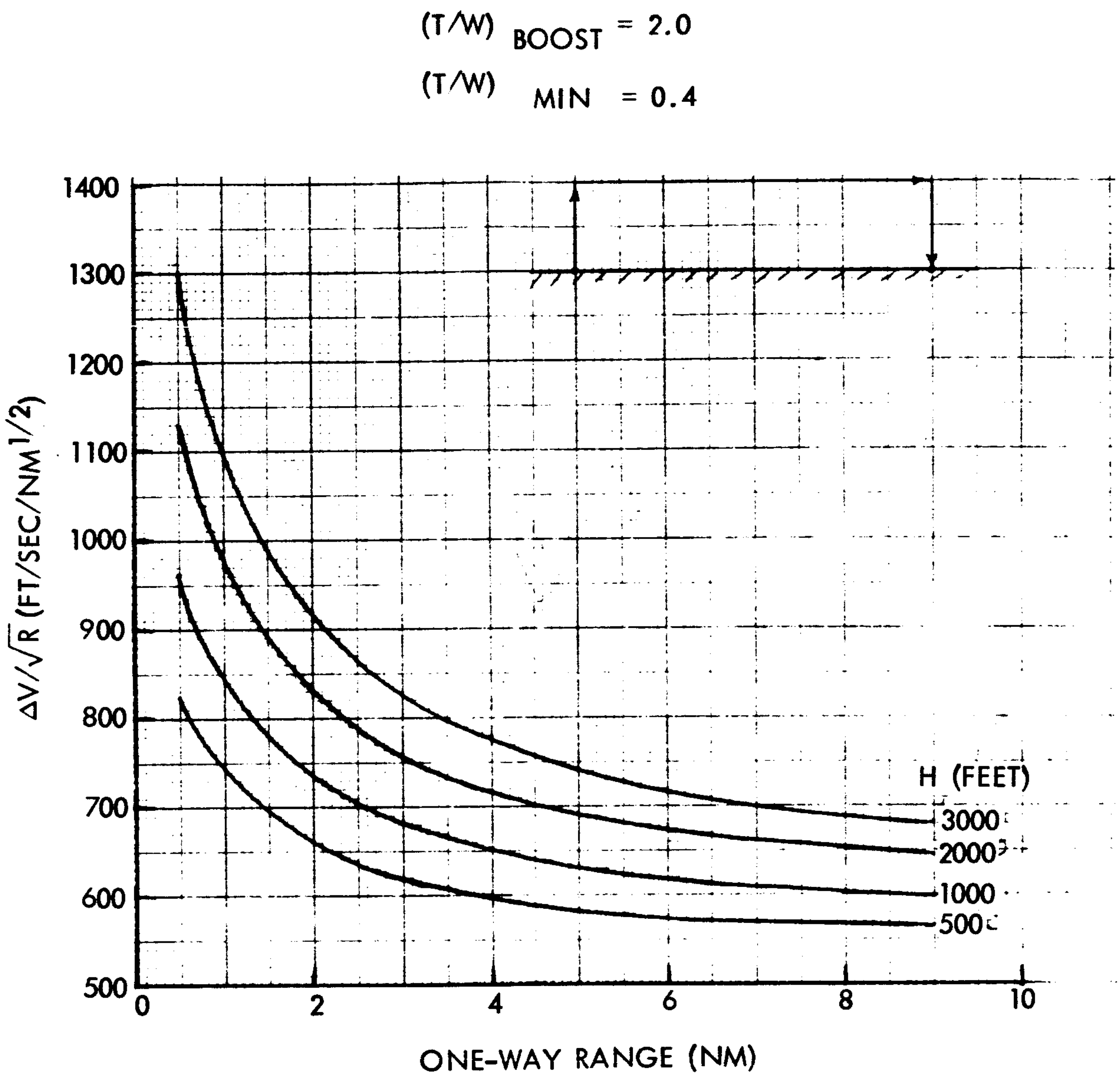


Figure 10. Normalized Characteristic Velocity Versus Range for Flat-Top Trajectories

Comparison of Constant-Altitude and Modified Ballistic Trajectories

A comparison of the normalized characteristic velocity for the constant-altitude trajectory and the modified ballistic trajectory is shown in Figure 11 as a function of boost T/W. This figure shows that in the region of boost T/W and throttling ratio of interest (T/W = 2.0 and throttling ratio of less than 10), $\Delta V/\sqrt{R}$ for the constant altitude trajectory is less than 10 percent greater than the modified ballistic trajectory values. Figure 12 compares the propellant required (percent of initial weight) as a function of one-way range for constant-altitude and modified ballistic trajectories. A boost T/W of 2.0 was assumed for the modified ballistic trajectory and a boost pitch angle of 45 degrees was assumed for the constant-altitude trajectory (T/W = 1.4 during boost). If the boost T/W for the modified ballistic trajectory had been 1.4, the two curves would be virtually identical.

Figures 13 and 14 show the radius of operation as a function of outbound and inbound payload for a total propellant load of 300 pounds for a vehicle with a dry weight of 180 pounds. Thirty pounds of propellant is assumed for contingency purposes and no hovers at takeoff and landing or trajectory variation propellant requirements are included. A comparison of these figures indicates that the modified ballistic mode provides improved radius with a boost T/W of 2.0. With a 300 pound inbound and outbound payload, the radius is 5.6 n mi for the constant-altitude trajectory and 7.2 n mi for the modified ballistic trajectory.

A realistic flight will have additional performance penalties associated with hovering type flight at takeoff and landing. Figure 15 presents the range penalty for the constant altitude trajectory as a function of hover time and cruise velocity, and Figure 16 shows the propellant weight (percentage of total weight) as a function of hover time. The data of Figure 16 and a 10 percent propellant trajectory variation penalty were applied to round trip modified ballistic and constant-altitude trajectories to determine the resulting round trip range (total loaded propellant of 300 pounds and a 180-pound vehicle dry weight). The results are shown in Figures 17 and 18 for the modified ballistic and constant altitude trajectories, respectively. With a 300-pound inbound and outbound payload, the maximum radius of operation is 5.0 n mi for modified ballistic flight and 4.0 n mi for constant-altitude flight. A comparison of Figures 13 and 14 with Figures 17 and 18 indicates the importance of reducing the pilot-induced trajectory variations and takeoff and landing hover times to low values.

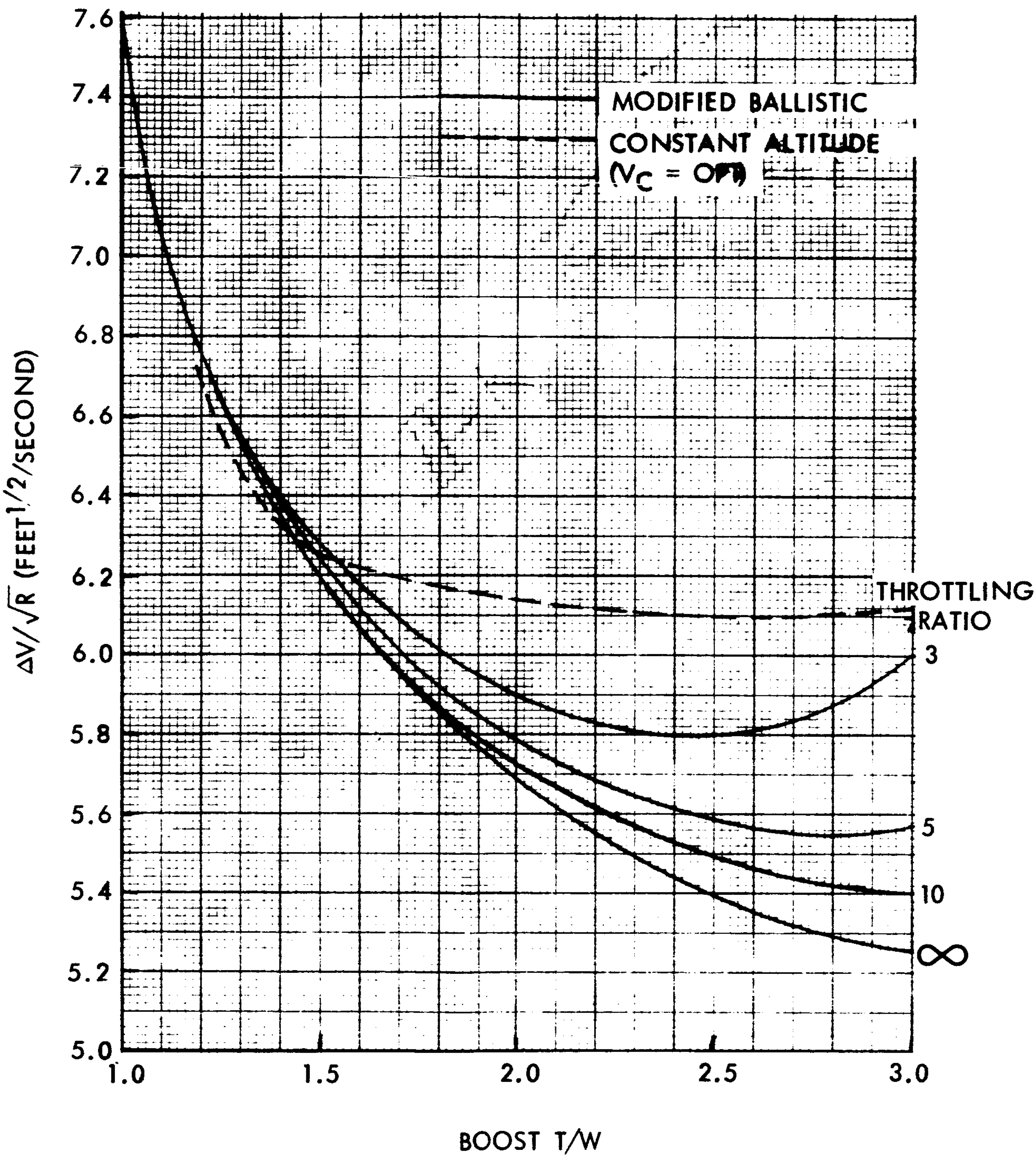


Figure 11. Sensitivity of Normalized Characteristic Velocity to Boost T/W

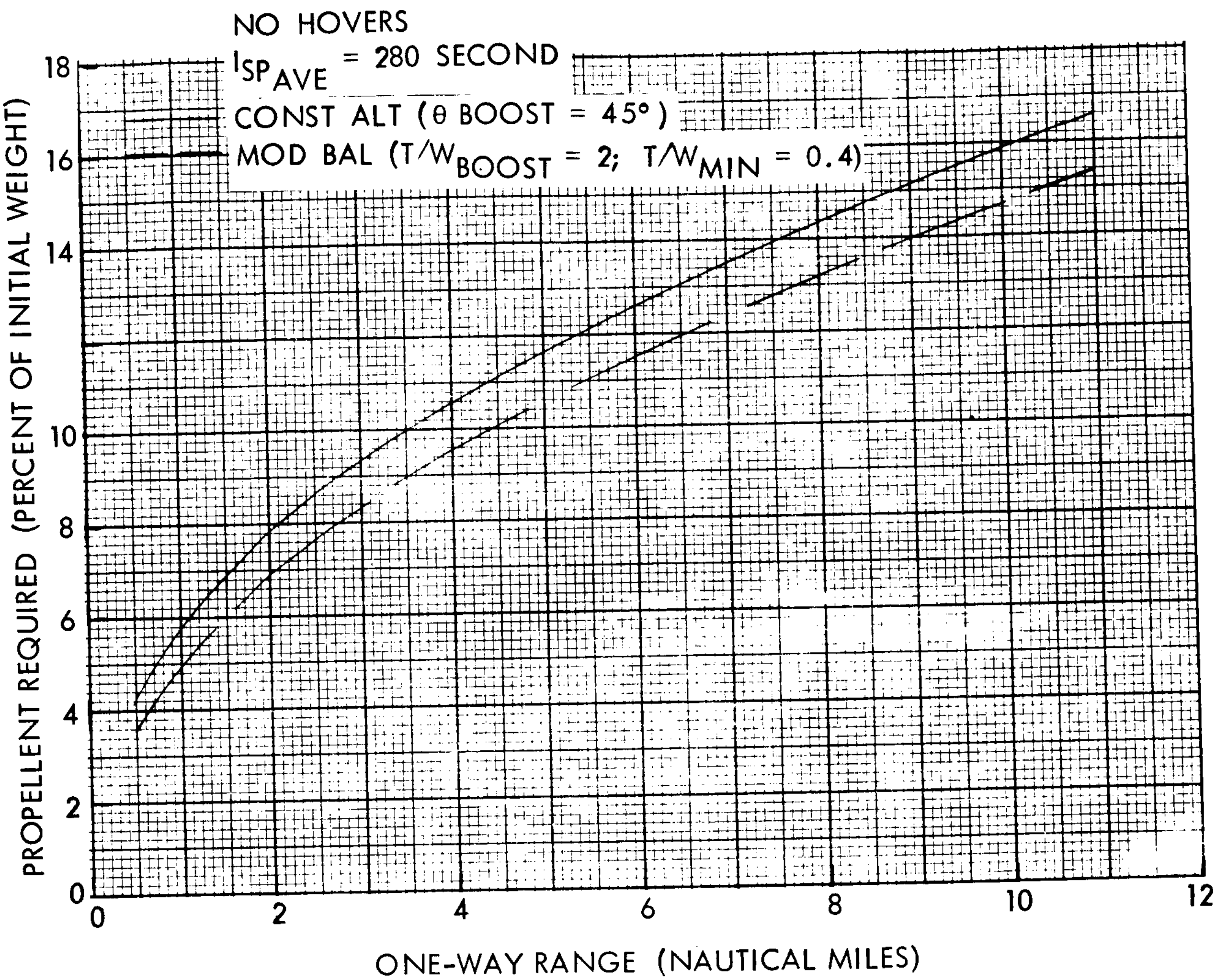


Figure 12. Propellant Requirements for Constant-Altitude and Modified-Ballistic Trajectories

COMPONENT	WEIGHT (POUNDS)
VEHICLE	180
PILOT	370
PROPELLANT	300
	850

RESERVES
30 LB PROPELLANT, CONTINGENCY
NO HOVERS
NO TRAJECTORY VARIATION

BOOST $T/W_{MIN} = 2$
THROTTLING RATIO = 5
PITCH OVER = 10°/SECOND

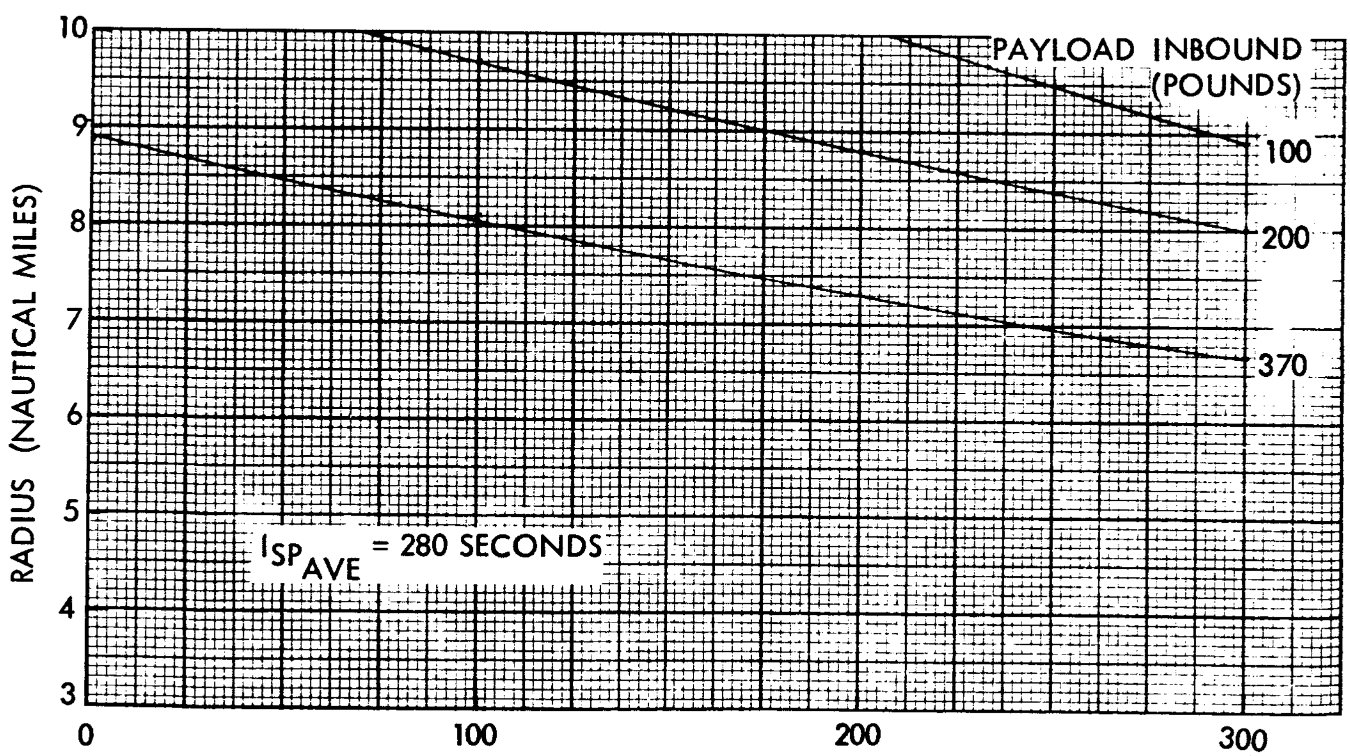


Figure 13. Modified Ballistic Trajectory Operational Radius, No Hover or Trajectory Variations

COMPONENT	WEIGHT (POUNDS)
VEHICLE	180
PILOT	370
PROPELLANT	300
	850

RESERVES
30 LB PROPELLANT CONTINGENCY
NO HOVERS
NO TRAJECTORY VARIATION

BOOST $T/W_{MIN} = 2$
THROTTLING RATIO = 5
CRUISE T/W = 1.41 AT $\theta = 45°$
PITCH OVER = 10°/SECOND

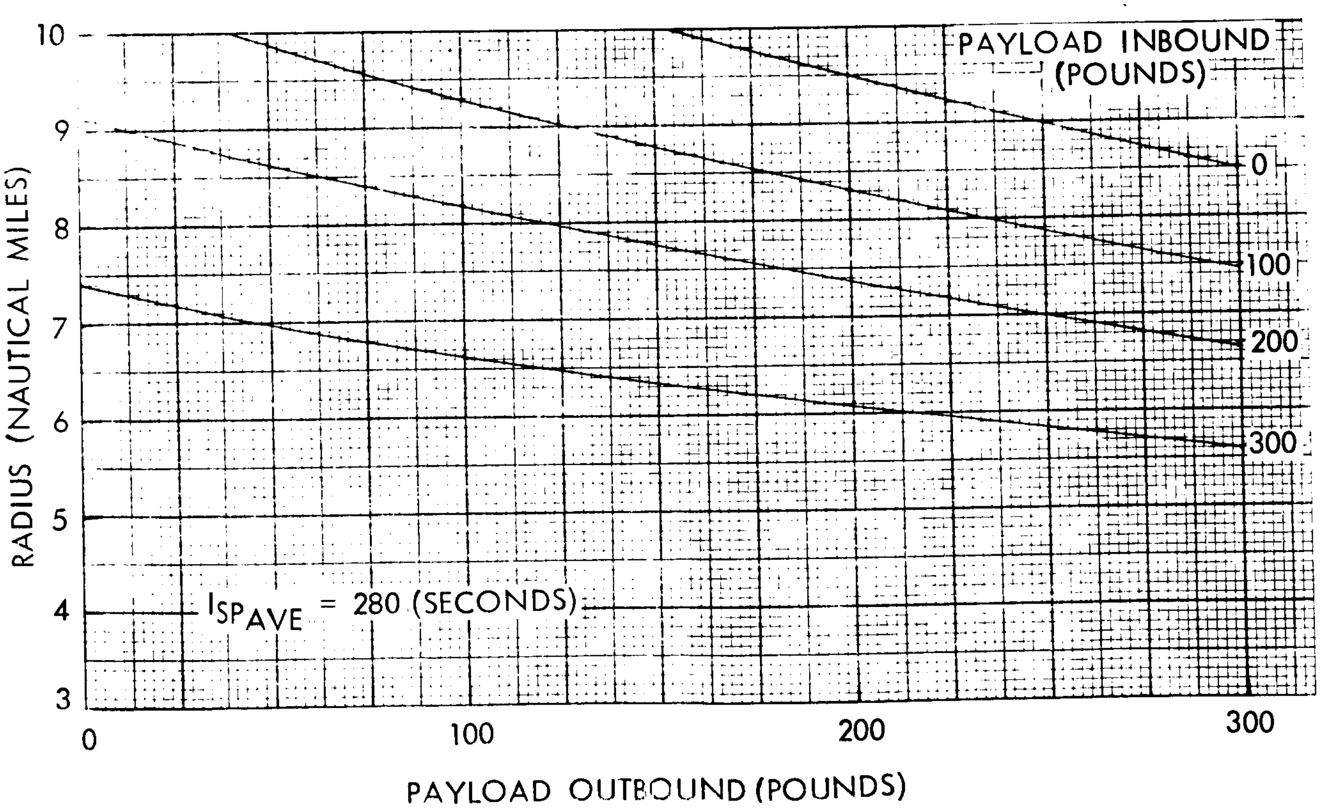


Figure 14. Constant-Altitude Trajectory Operational Radius, No Hover or Trajectory Variations

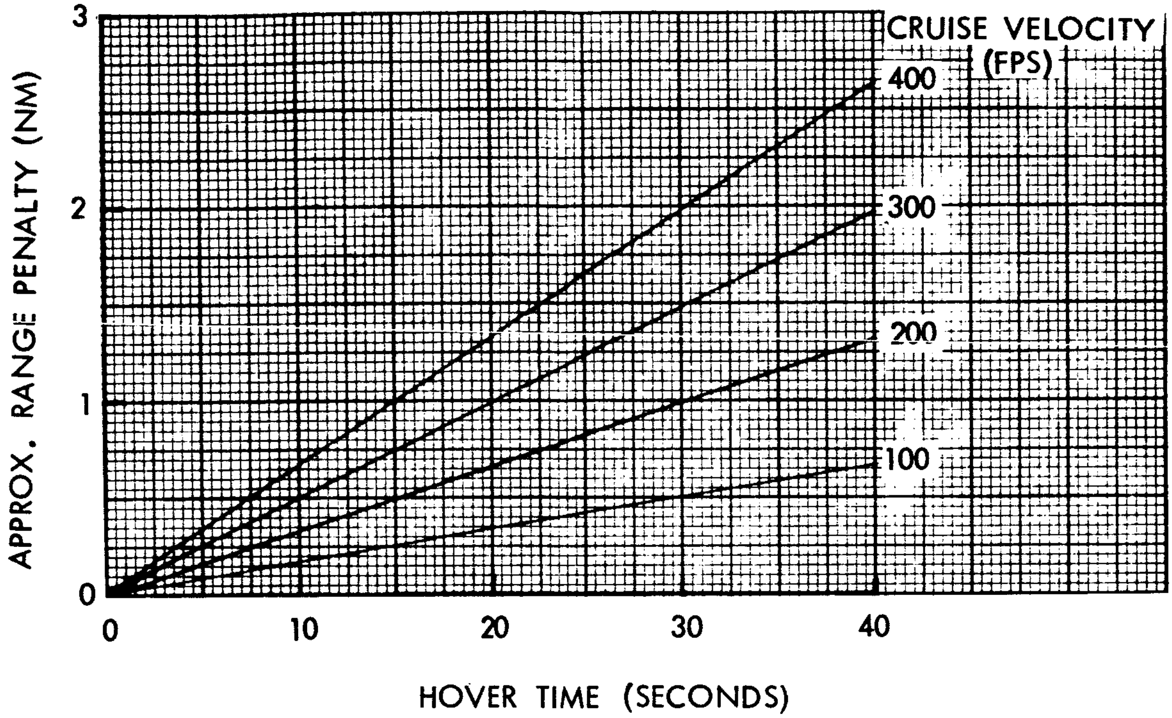


Figure 15. Constant-Altitude Trajectory, Range Penalty for Hover Time

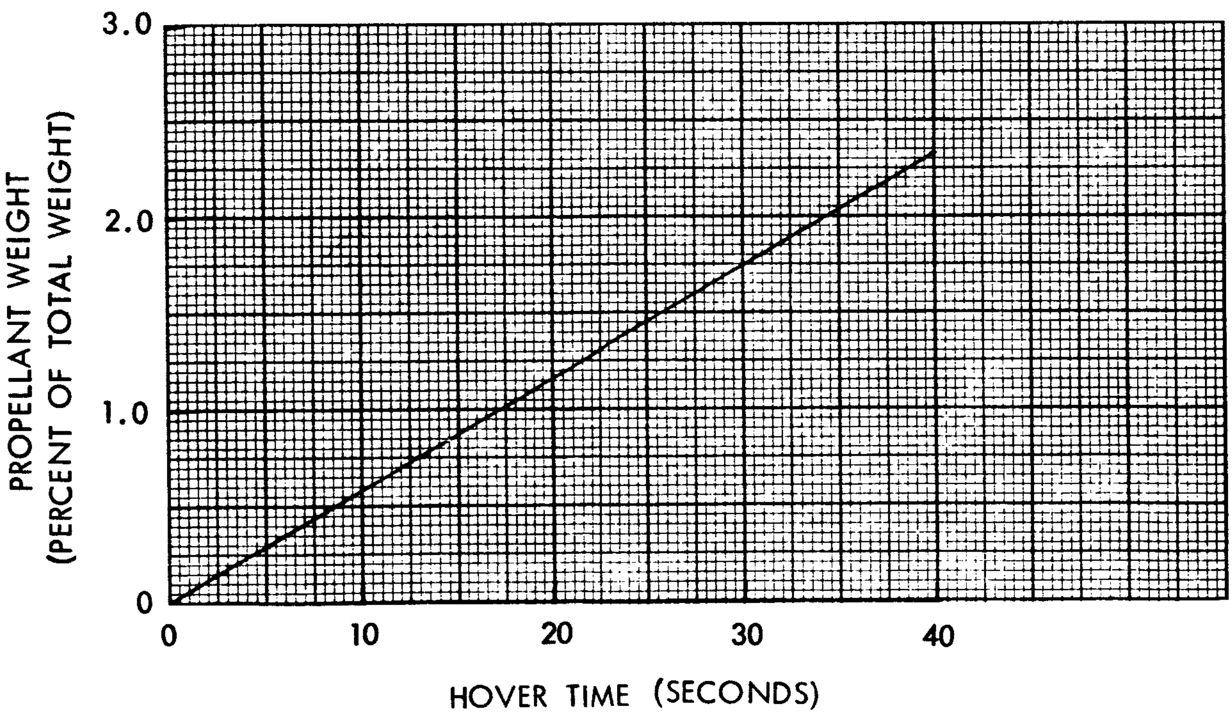


Figure 16. Hover Propellant Requirements

COMPONENT	WEIGHT (POUNDS)
VEHICLE	180
PILOT	370
PROPELLANT	300
	850

RESERVES
5-SECOND TAKEOFF HOVER
10-SECOND LANDING HOVER
10 PERCENT PROPELLANT, TRAJECTORY VARIATION
30 POUND PROPELLANT, CONTINGENCY

BOOST $T/W_{MIN} = 2$
THROTTLE RATIO = 5
PITCH OVER = 10°/SECOND

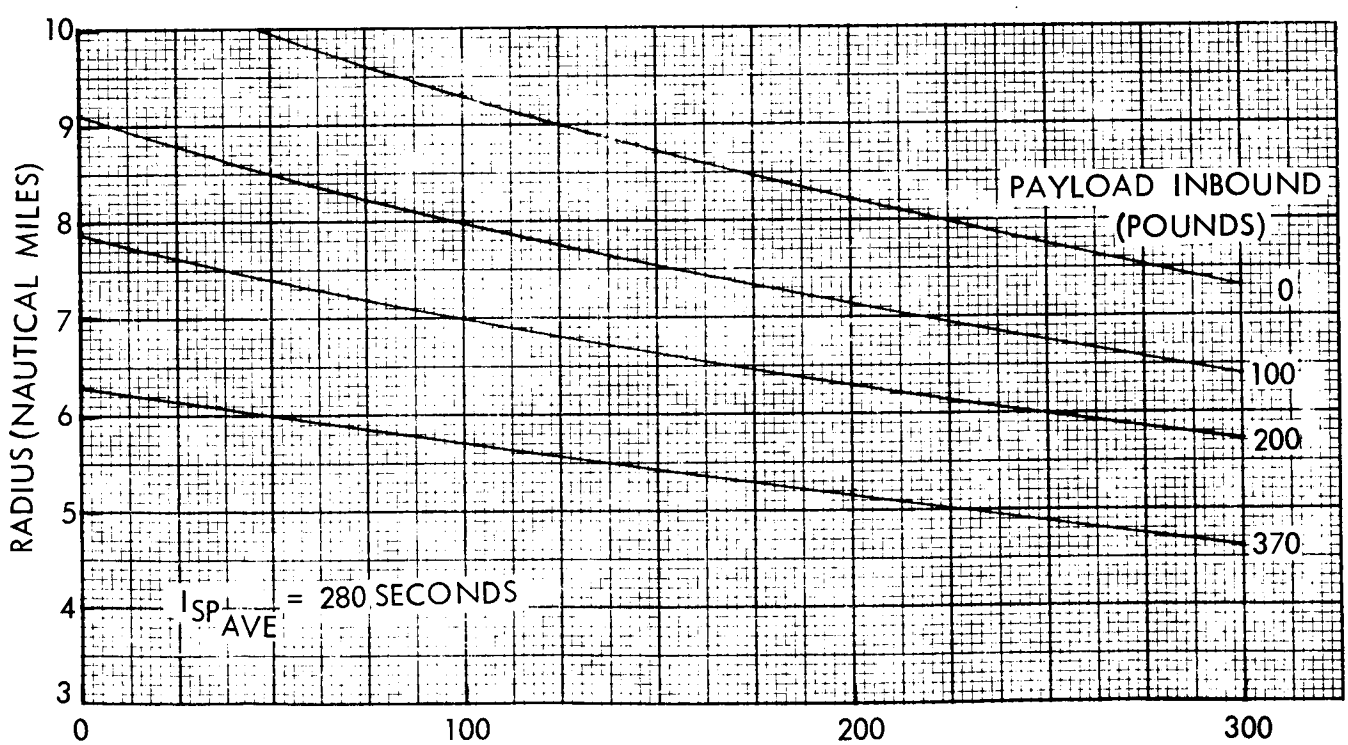


Figure 17. Modified-Ballistic Trajectory Operational Radius, Including Hovers and Trajectory Variations

COMPONENT	WEIGHT (POUNDS)
VEHICLE WEIGHT	180
PILOT	370
PROPELLANT	300
	850

RESERVES
- 5-SECOND TAKEOFF HOVER
- 10-SECOND LANDING HOVER
- 10 PERCENT PROPELLANT, TRAJECTORY VARIATION
- 30 POUND PROPELLANT, CONTINGENCY

BOOST $T/W_{MIN} = 2$
THROTTLE RATIO = 5
CRUISE T/W = 1.41 AT = 45°
PITCH OVER = 10°/SECOND

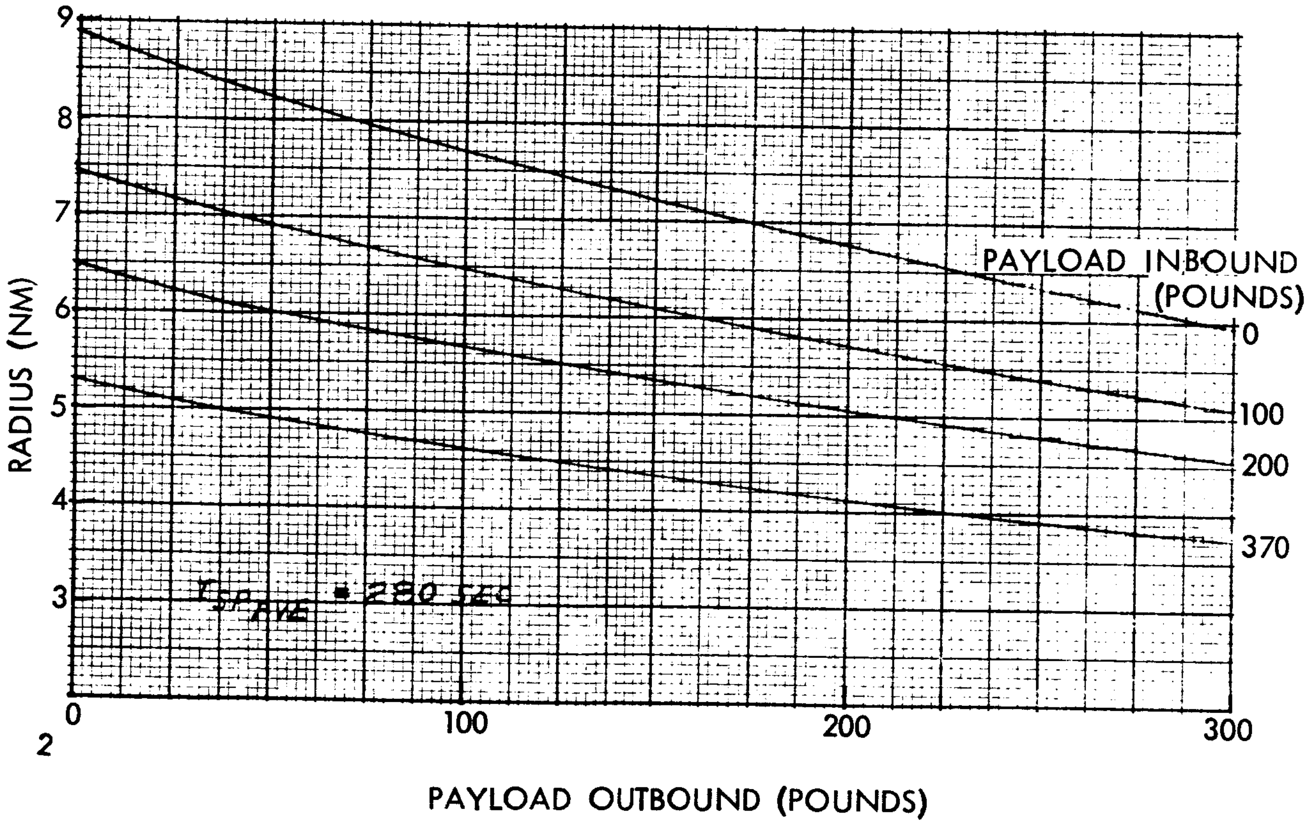


Figure 18. Constant-Altitude Trajectory Operational Radius, Including Hovers and Trajectory Variations

BASELINE FLIGHT PROFILES

Three general missions were analyzed with the aid of a digital computer program. They consist of (1) a 0.5 n mi radius round trip, (2) maximum radius round trip, and (3) a triangular flight. The primary purpose of this study was to obtain typical thrust profile data for propulsion system analysis.

A list of five constant-altitude sorties with their trajectory parameters is given in Table 1. A five-second takeoff hover, 40-second landing hover, and a 400-pound maximum thrust were assumed on each sortie. The first two sorties are familiarization flights. If the landing hover time could be reduced to 20 seconds on sorties 3 and 5, then the radius could be increased by approximately 1 n mi. This is also true for Figure 19, which describes the nominal maximum range constant-altitude trajectory and gives a weight breakdown for the assumed baseline mission. A constant flight path angle was used in the deboost phase, but this resulted in negligible performance differences when compared to the symmetrical model used in the theoretical analysis.

Thrust Time Curves for Nominal Missions

Figures 20 through 22 indicate the thrust vs. time profiles for a 300 lb maximum thrust constant altitude trajectory for each of the three general missions. Figure 23 shows the thrust vs. time profile for a 400-pound-thrust maximum range modified ballistic trajectory. Although the initial boost thrust is 400 pounds, the deboost thrust was limited to 300 pounds to provide margin for an engine failure during the deboost phase (four-engine configuration). A linear transition between the program's point interval was assumed.

Table 2 compares a summary of the three missions for the constant-altitude and modified ballistic modes. The trajectories assumed a 400-pound maximum thrust and a 5-second takeoff and 40-second landing hover. The modified ballistic mode proved to be slightly more economical in terms of range for propellant expended in all of the flights.

Sensitivity Analysis

The maximum range constant-altitude and modified ballistic missions were used as the nominal trajectories for the sensitivity analysis. The flight parameters of the nominal trajectories were perturbed and fed into the digital computer program to obtain the sensitivities. Table 3 compares the error sensitivities of the constant-altitude and modified ballistic modes. The modified ballistic profile is shown to be extremely sensitive to pilot error. The tip angle and boost time errors are the more critical parameters in both modes.

Table 1. Constant-Altitude Sortie (400-Pound Maximum Thrust)

Trajectory Characteristics	Sorties				
	1* (One stop)	2* (One stop)	3 (One stop)	4 (Triangular)	5 (One stop)
Radius (n mi)	0.5	0.5	5.0	1.5	5.0
Distance transversed (n mi)	1.0	1.0	10.0	4.5	10.0
Propellant consumed** (earth pounds)	138.8	138.8	269.6	274.4	269.6
Time (seconds)	210.9	210.9	406.0	424.1	406.0
Maximum altitude (feet)	300	300	600	400	600
Cruise velocity (ft/sec)	110	110	320	200	320

*Familiarization flights
**Includes 40-second landing hover

Weight (pounds)	
Vehicle dry weight	250
Pilot	370
Propellant	300
Payload	100
Total	1020

1 5-SECOND HOVER
2 PITCH 8 DEGREES/SECOND TO 45° AT 250 POUNDS THRUST
3 400 POUNDS THRUST BOOST FOR 21 SECONDS
4 80 POUNDS THRUST COAST TO $\gamma = 0°$
5 ACCELERATE TO 320 FPS AT $\theta = 45°$
6 CRUISE AT 320 FPS
7 DECELERATE TO SEGMENT 4 END VELOCITY AT $\theta = -45°$
8 80 POUNDS THRUST DECOAST TO $\gamma = -20°$
9 DEBOOST AT CONSTANT $\gamma = -20°$
10 40-SECOND LANDING HOVER

COMPONENT	WEIGHT (POUNDS)
VEHICLE	250
PILOT	370
PROPELLANT	300
PAYLOAD	100
TOTAL	1020

270 POUNDS USEABLE PROPELLANT
280 SECONDS AVERAGE I_{SP}

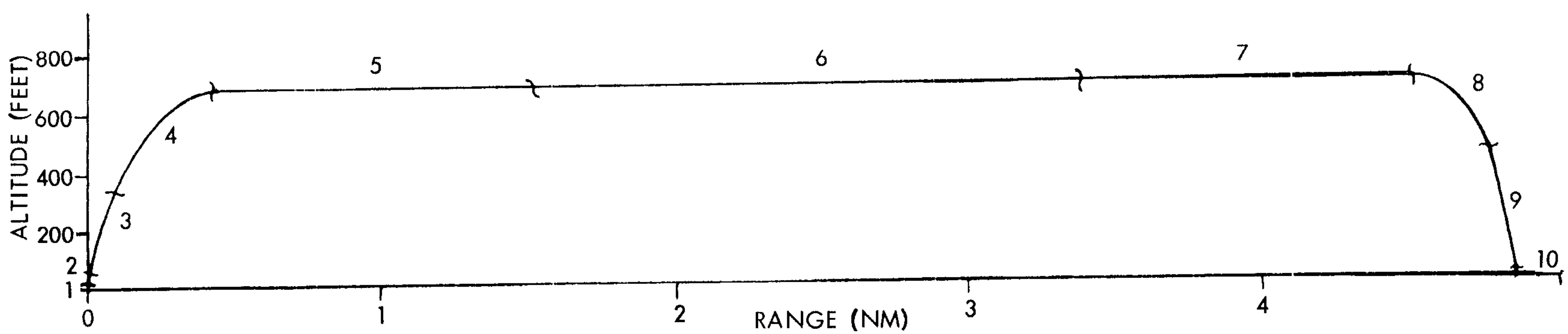


Figure 19. Nominal Constant-Altitude Maximum-Range Trajectory

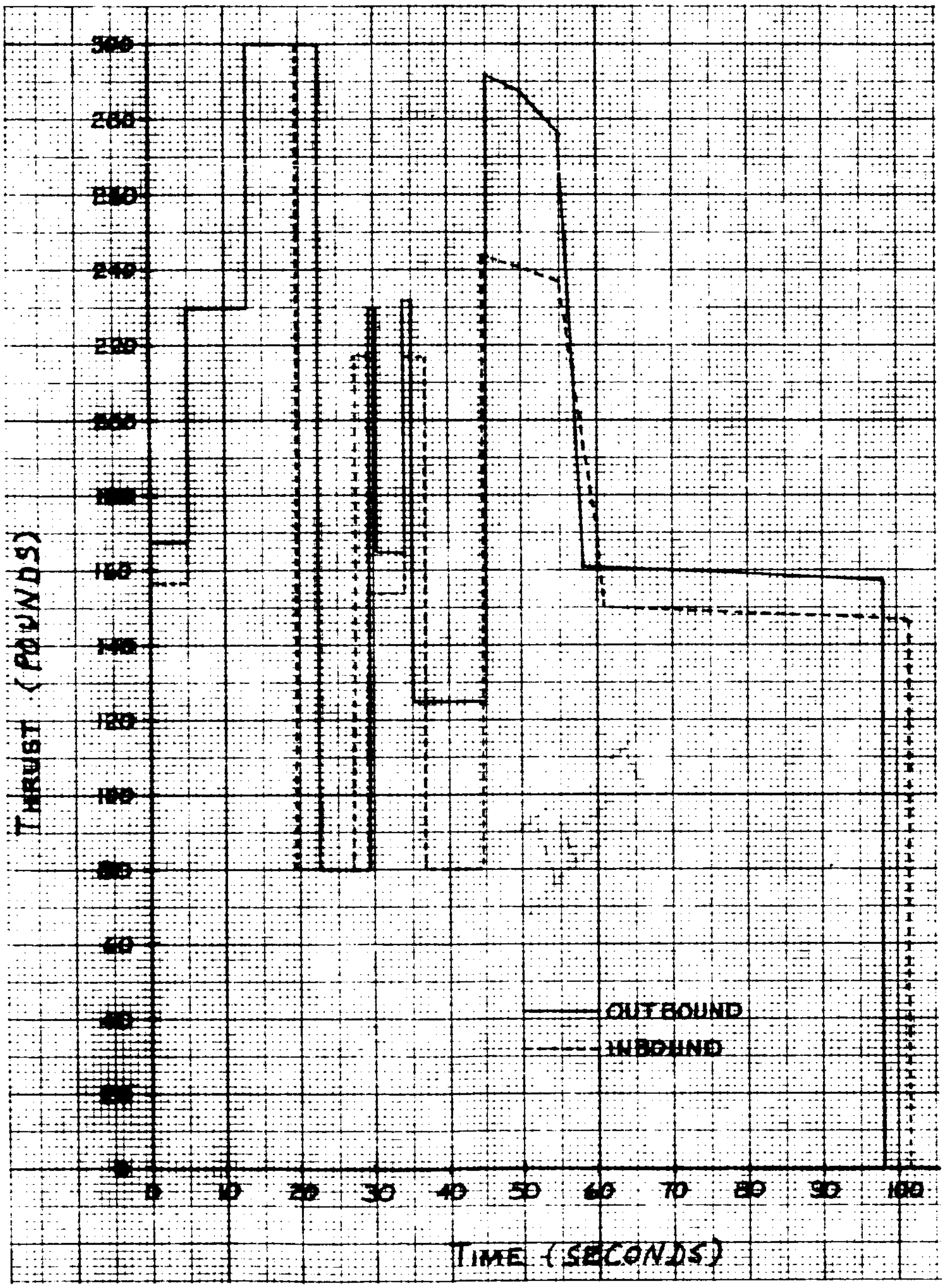


Figure 20. Constant-Altitude Mode, Thrust Versus Time for 0.5-NM-Range Sortie With 300-Pound Maximum Thrust Engine

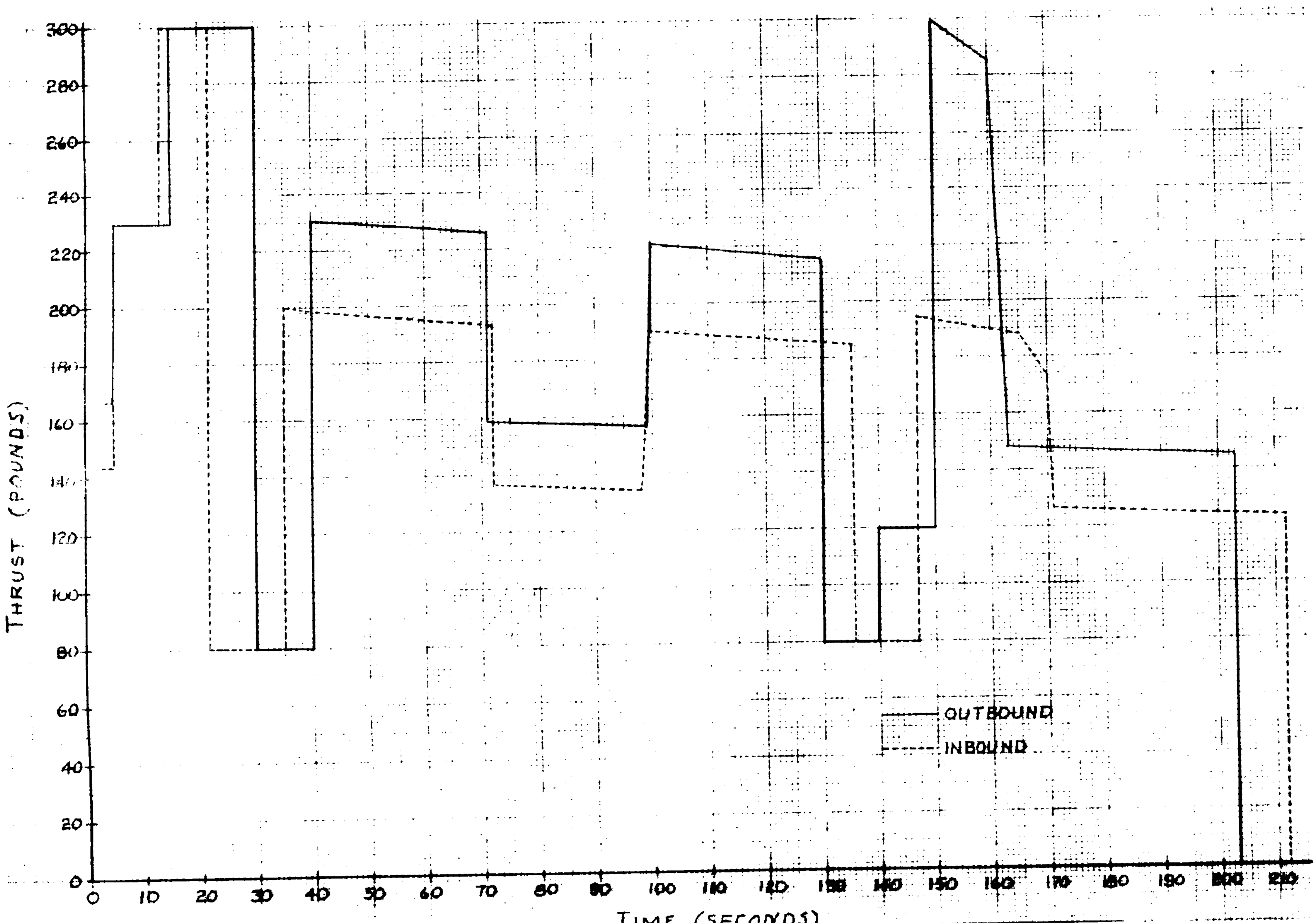


Figure 21. Constant-Altitude Mode, Thrust-Versus-Time Profile for 5-NM-Range Sortie With 300-Pound Maximum Thrust Engine - Baseline Vehicle and Assumptions

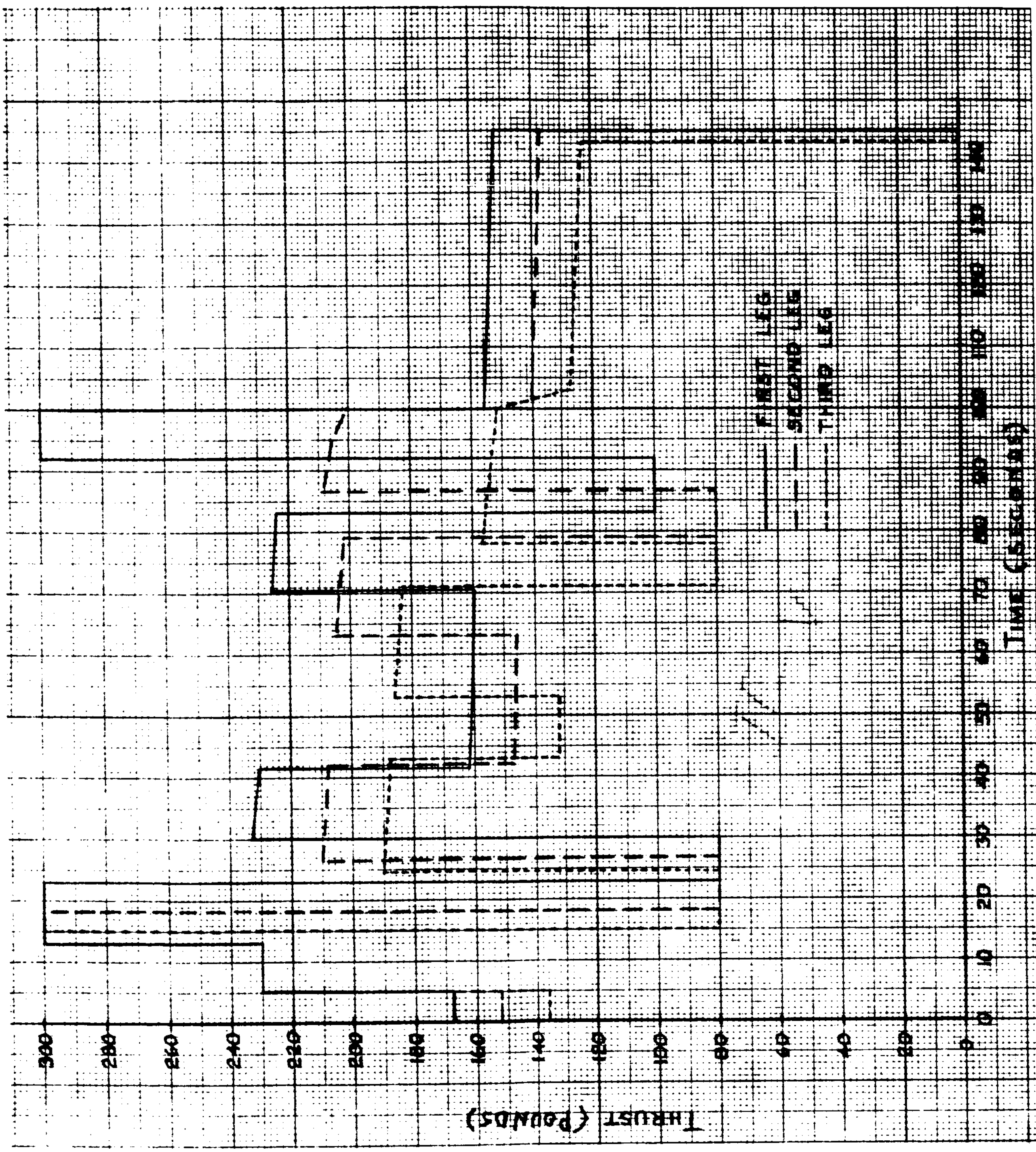


Figure 22. Constant-Altitude Mode, Thrust-Versus-Time Profile for Triangular Sortie With 300-Pound Maximum Thrust Engine - Baseline Vehicle and Assumptions

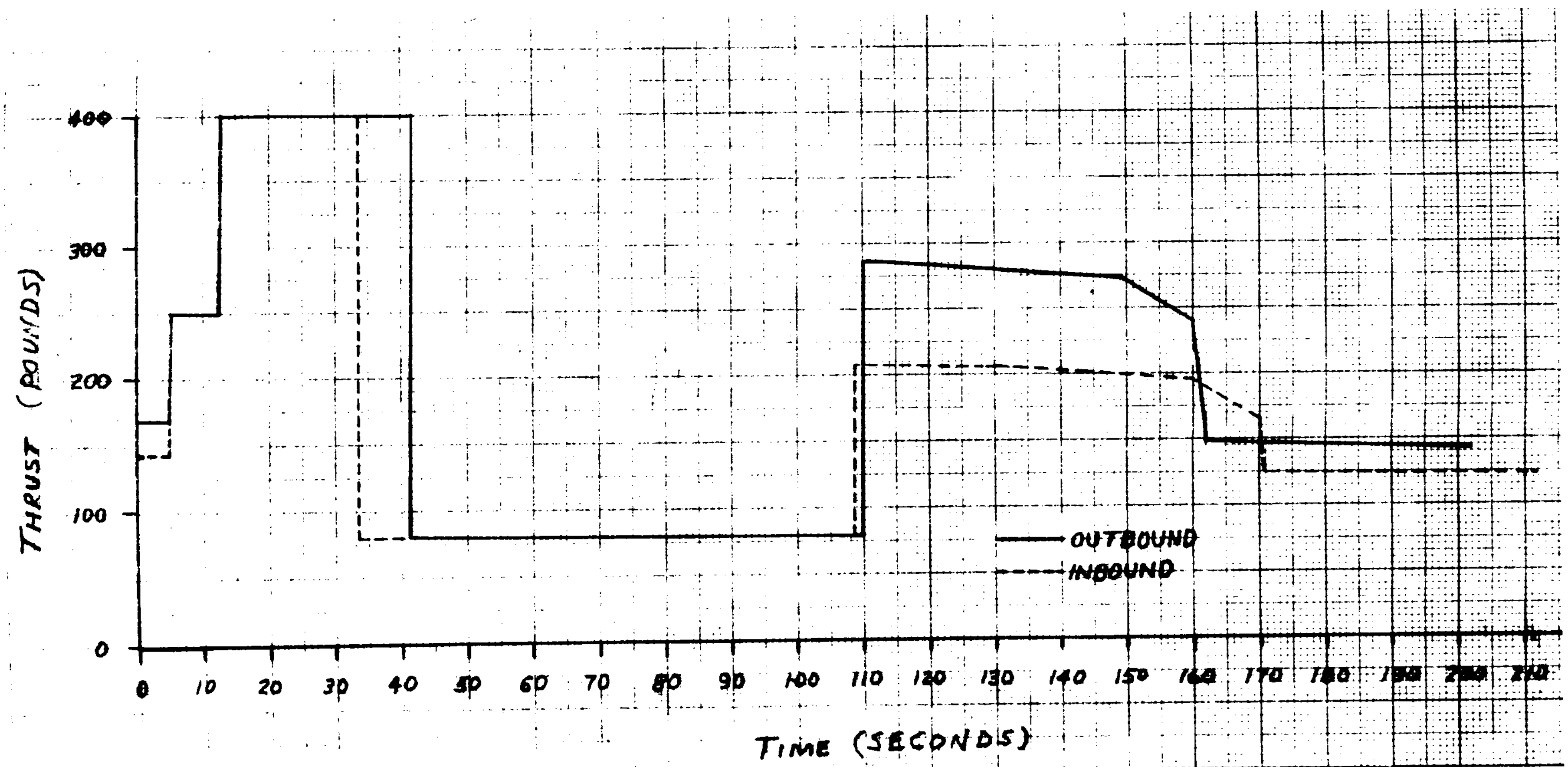


Figure 23. Modified-Ballistic Mode, Thrust-Versus-Time Profile for 5.6-NM-Range Sortie With 400-Pound Maximum Thrust Engine - Baseline Vehicle and Assumptions

Table 2. Summary of Missions (400-Pound Maximum Thrust)

Mission	Leg	Radius (n mi)	Propellant* (pounds)	Time (seconds)
0.5 n mi	1	0.5 (0.5)**	71.2 (67.6)	104.6 (100.1)
	2	0.5 (0.5)	67.6 (65.3)	106.3 (103.9)
Total		1.0 (1.0)	138.8 (132.9)	210.9 (204.0)
Maximum range	1	4.95 (5.69)	143.3 (143.3)	137.1 (140.7)
	2	5.02 (5.54)	126.3 (127.7)	134.0 (143.3)
Total		9.97 (11.23)	269.6 (271.0)	271.1 (284.0)
	1	1.40 (1.91)	97.0 (98.5)	137.1 (140.7)
	2	1.67 (1.78)	88.8 (89.9)	134.0 (143.3)
	3	1.25 (1.73)	81.6 (83.6)	143.4 (148.2)
Total		4.32 (5.42)	267.4 (272.0)	414.5 (432.2)

*Includes 40-second landing hover
**( ) Indicates modified ballistic trajectory

Weight (pounds)

Vehicle dry weight	250
Pilot	370
Propellant	300
Payload	100
Total	1,020

Table 3. Error Sensitivities Based on Maximum Range Mission

Variable	Nominal Value	Dispersion	Range $\Delta R/\Delta\xi$	Maximum Altitude $\Delta Hmax/\Delta\xi$
Boost thrust	400 lbs	±10	±13 (±264)*ft/lb	±4 (±39) ft/lb
Boost time	21 (41.8) sec	±2	±374 (±2242) ft/sec	±95 (±281) ft/sec
Coast thrust	80 lbs	±5	±20 (±231) ft/lb	±3 (±18) ft/sec
Initial Weight	1020 lbs	±30	∓12 (∓147) ft/lb	∓3 (∓21) ft/lb
Tip angle, θ	45 deg	±10	∓625 (∓1289) ft/deg	∓42 (∓368) ft/deg
Tip rate, $\dot{\theta}$	8 deg/sec	±4	±130 (±1663) ft/$\frac{deg}{sec}$	±36 (±173) ft/$\frac{deg}{sec}$
Cruise Velocity	320 (---) ft/sec	±25	±130 (---) ft/fps	0 (---) ft/fps

*(   ) Indicates modified ballistic trajectory

Weight (pounds)	
Vehicle dry weight	250
Pilot	370
Propellant	300
Payload	100
Total	1,020

Figure 24 shows the penalty in terms of characteristic velocity for a flat-top trajectory as a function of the altitude.

The effect of errors in pitch angle and pitch timing (early pitch) on constant altitude performance was determined. For an optimum boost trajectory, the normalized characteristic velocity, $\Delta V/\sqrt{R}$ is equal to 6.22. If it is assumed that without instruments, the astronaut can determine and hold pitch angle to ±10 degrees of an ideal 45 degrees, then the error in terms of $\Delta(\frac{\Delta V}{\sqrt{R}}) = 0.38$. By having instruments with which he can determine and hold the 45-degree pitch angle to ±2 degrees, the error is reduced to $\Delta(\frac{\Delta V}{\sqrt{R}}) = 0.06$. Figure 25 shows the effect for various flight ranges of a pitchover that is performed 5 seconds too early. It is significant that the effect of this source of error is relatively minor, particularly for flights longer than 4 n mi range.

It is considered unlikely that the astronaut would fly to the desired constant altitude utilizing either a pure modified ballistic ascent and descent trajectory or a vertical rise and descent (flat top) trajectory. In order to gain an appreciation of what a "realistic" normalized characteristic velocity would be (as a function of range), the relationships of $\Delta V/\sqrt{R}$ vs. range for a base-line flat-top trajectory and for an optimum constant-altitude trajectory which utilizes a modified ballistic trajectory ascent to and descent from altitude were "averaged".

Figure 26 shows the result of this averaging under the assumption that the altitude would vary from 300 feet for short ranges to 500 feet long ranges. Figure 26 permits similar averaging for other altitude assumptions. It is considered that the averaged curve shown in Figure 26 would be fairly realistic. This curve was then plotted as the basic curve in Figure 27. Added to the basic curve was the effect of a 5-second error in pitch timing, and the effect of error with and without pitch attitude instruments. These curves indicate the approximate normalized characteristic velocity requirements anticipated.

PERFORMANCE OF SELECTED DESIGN CONCEPT

Figures 28 through 32 show the performance capability of the selected design concept for various payload conditions and reserve propellant assumptions using a constant altitude trajectory. A boost pitch angle of 45 degrees was assumed along with a flight altitude of 500 feet. Figure 33 is a cross plot that shows the range attainable with a fixed outbound/inbound payload for a given reserve propellant quantity assumption. These data are presented to illustrate the parametric characteristics of the selected concept but do not represent the probable performance capability.

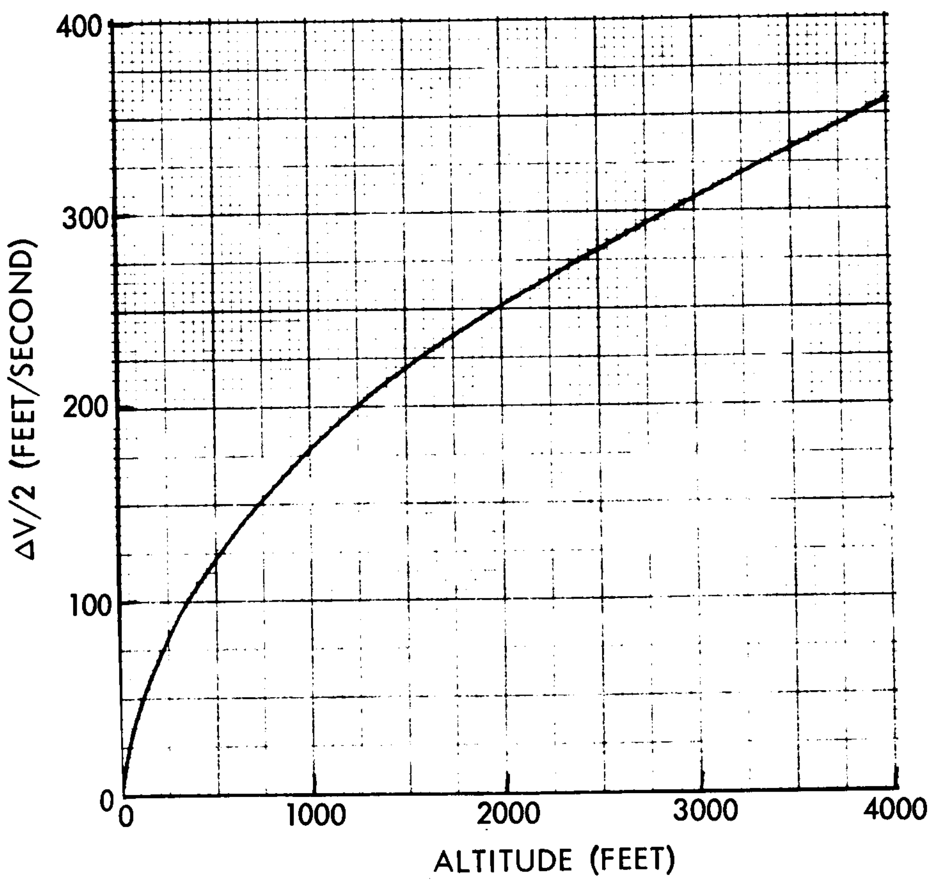


Figure 24. Characteristic Velocity Penalty for Flat-Top Trajectories

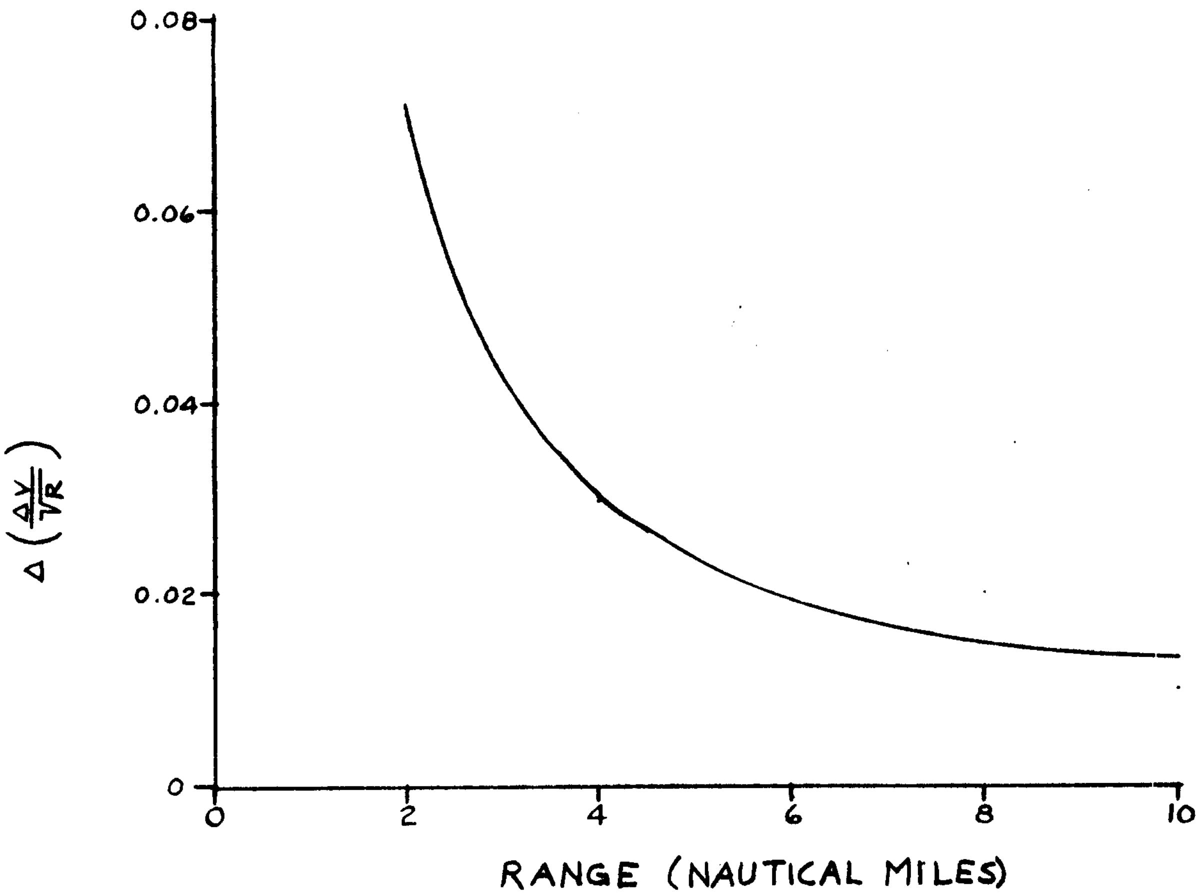


Figure 25. Effect of Pitch-Timing Error - 5 Seconds Too Early (-26.5-Foot-Per-Second Error)

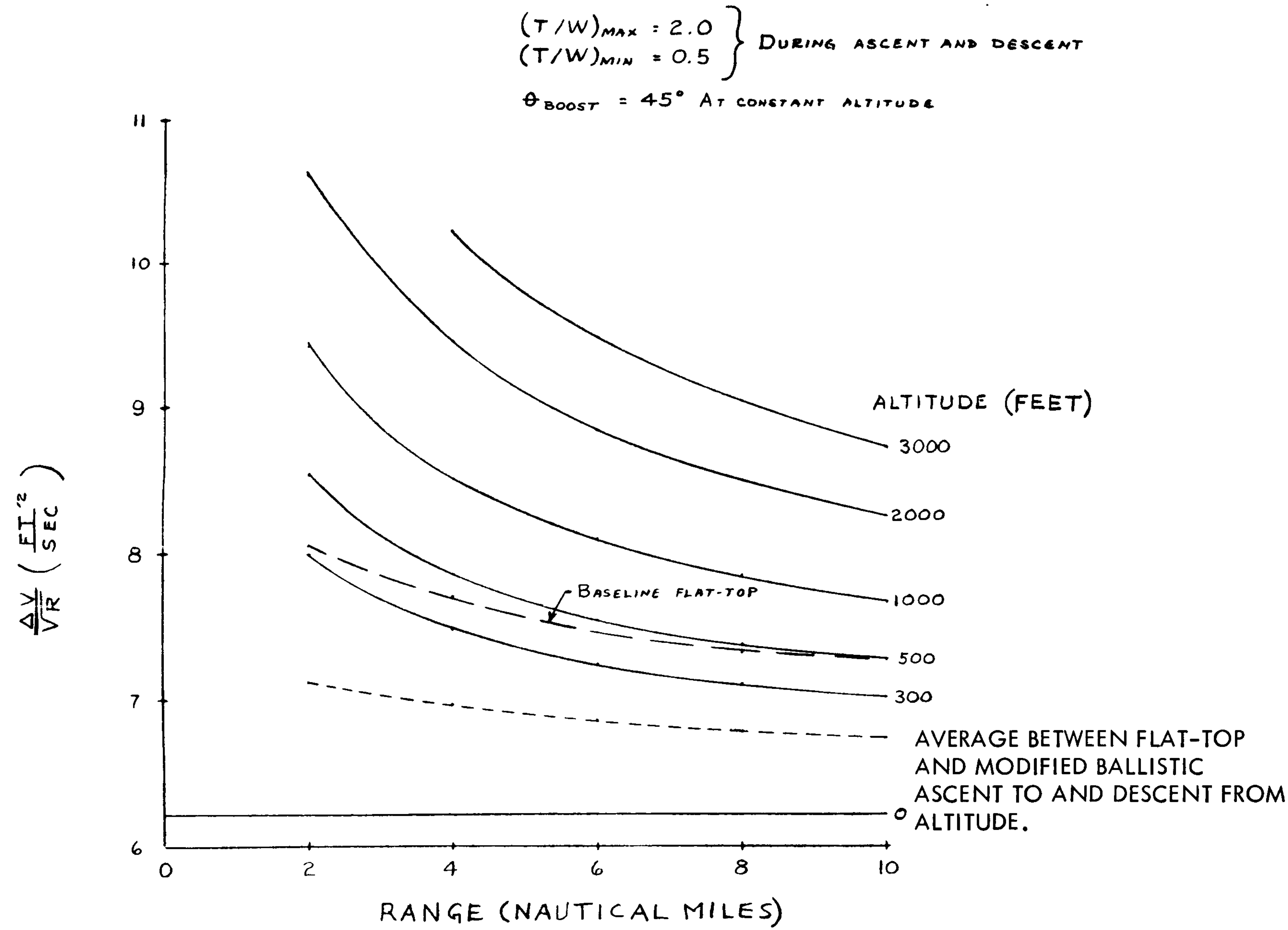


Figure 26. Effect of Flight Altitude on ΔV Required

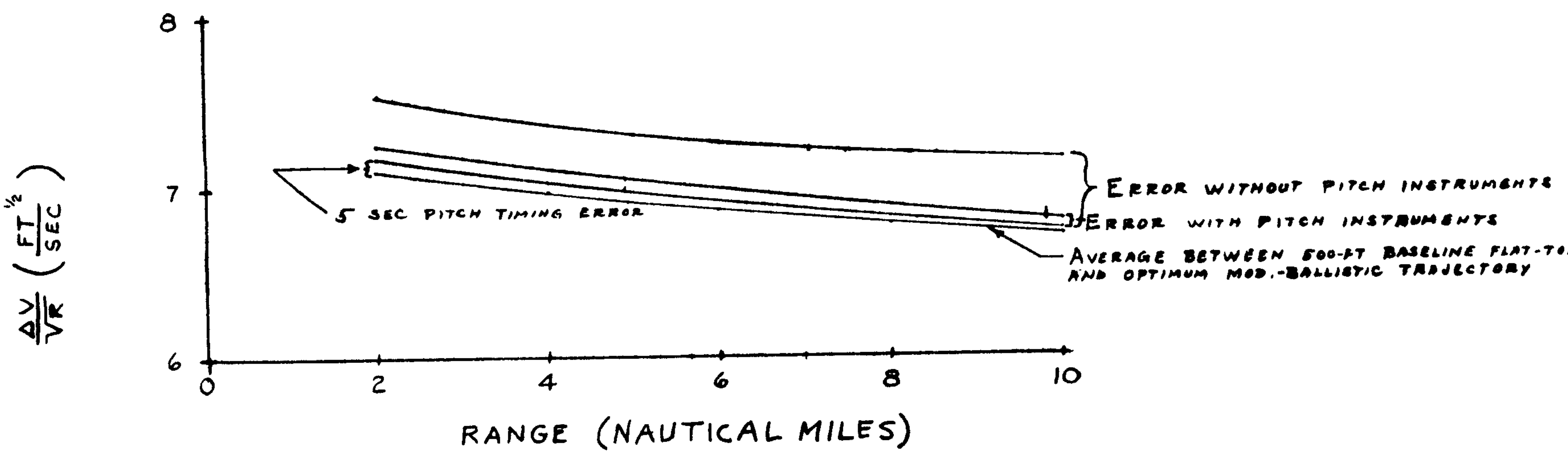


Figure 27. Typical Normalized Characteristic Velocity Required

COMPONENT	WEIGHT (POUNDS)
VEHICLE	300
PILOT	370
PROPELLANT	300
	970

RESERVES: NONE

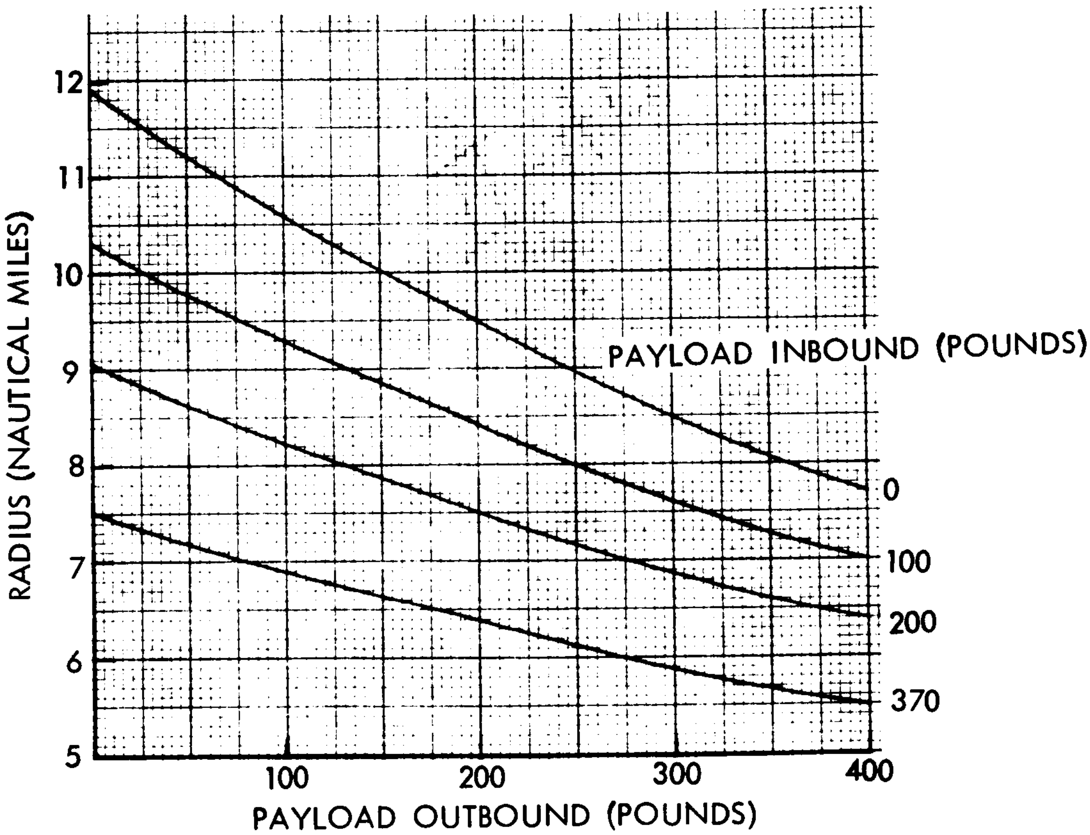


Figure 28. Constant-Altitude Trajectory Operational Radius, No Reserves

COMPONENT	WEIGHT (POUNDS)
VEHICLE	300
PILOT	370
PROPELLANT	300
	970

RESERVES: 50 POUND PROPELLANT

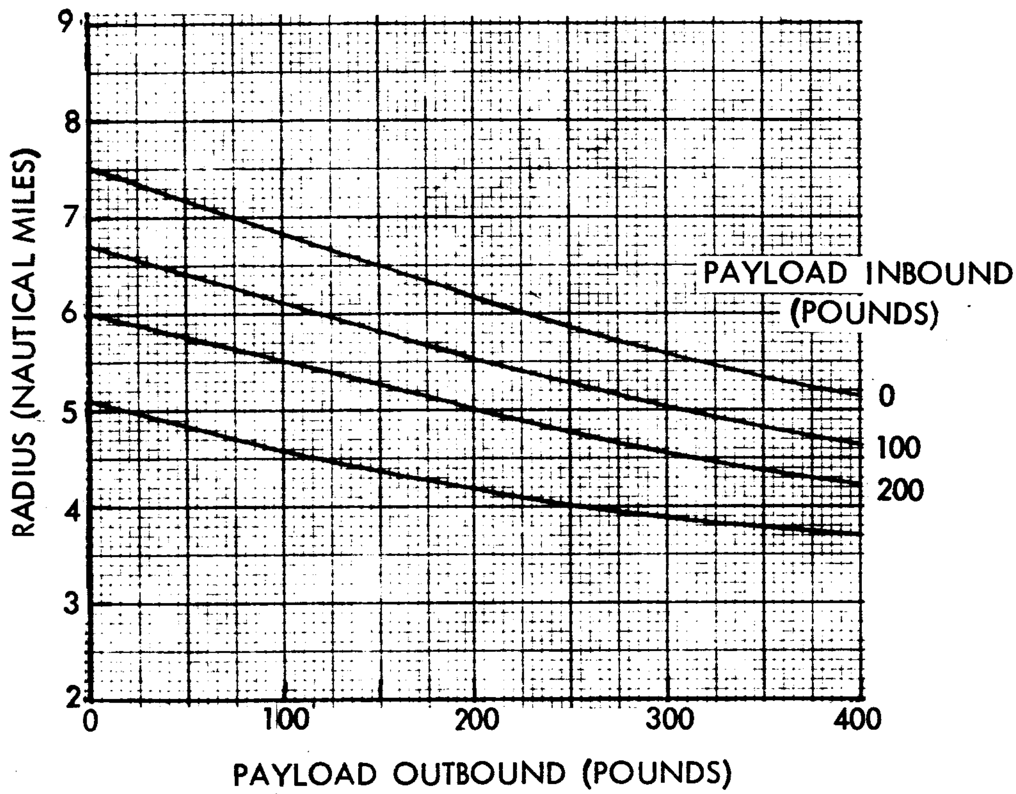


Figure 29. Constant-Altitude Trajectory Operational Radius, 50-Pound Propellant Reserve

COMPONENT	WEIGHT (POUNDS)
VEHICLE	300
PILOT	370
PROPELLANT	300
	970
RESERVES:	100-POUNDS PROPELLANT

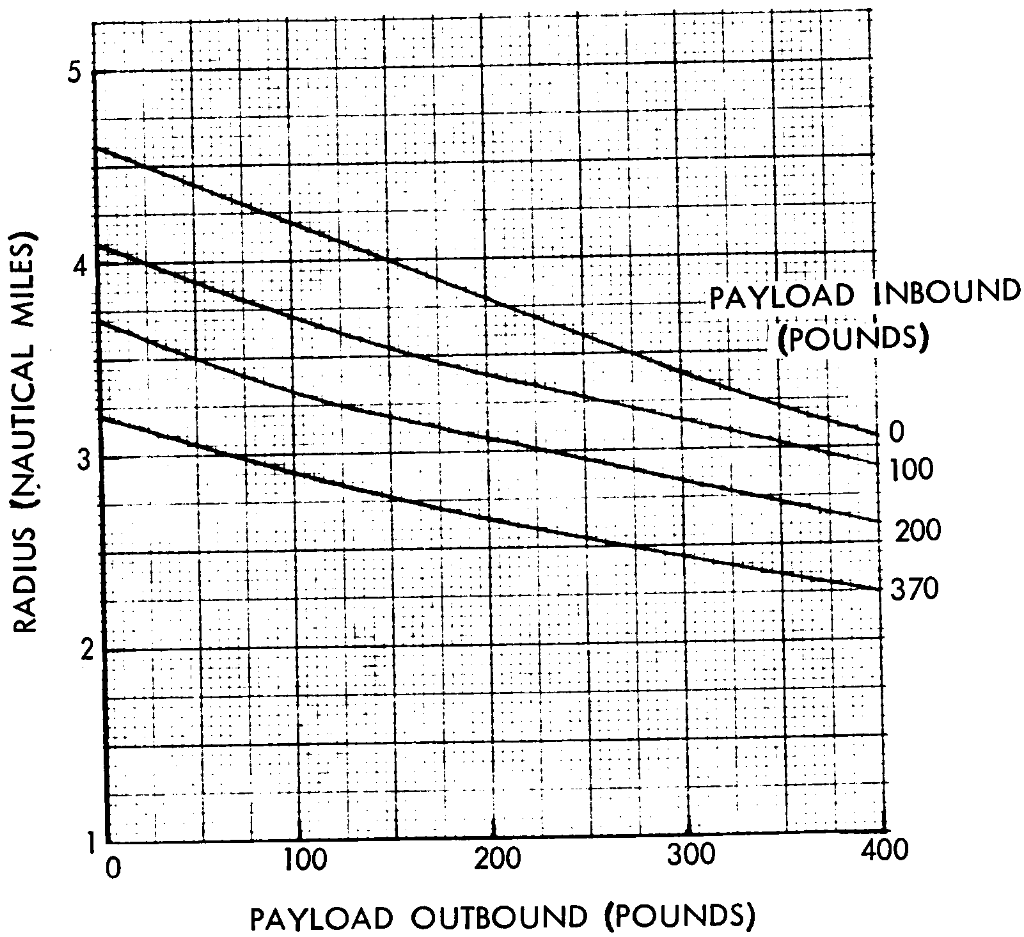


Figure 30. Constant-Altitude Trajectory Operational Radius, 100-Pound Propellant Reserve

COMPONENT	WEIGHT (POUNDS)
VEHICLE	300
PILOT	370
PROPELLANT	300
	970

RESERVES: 150 POUNDS PROPELLANT

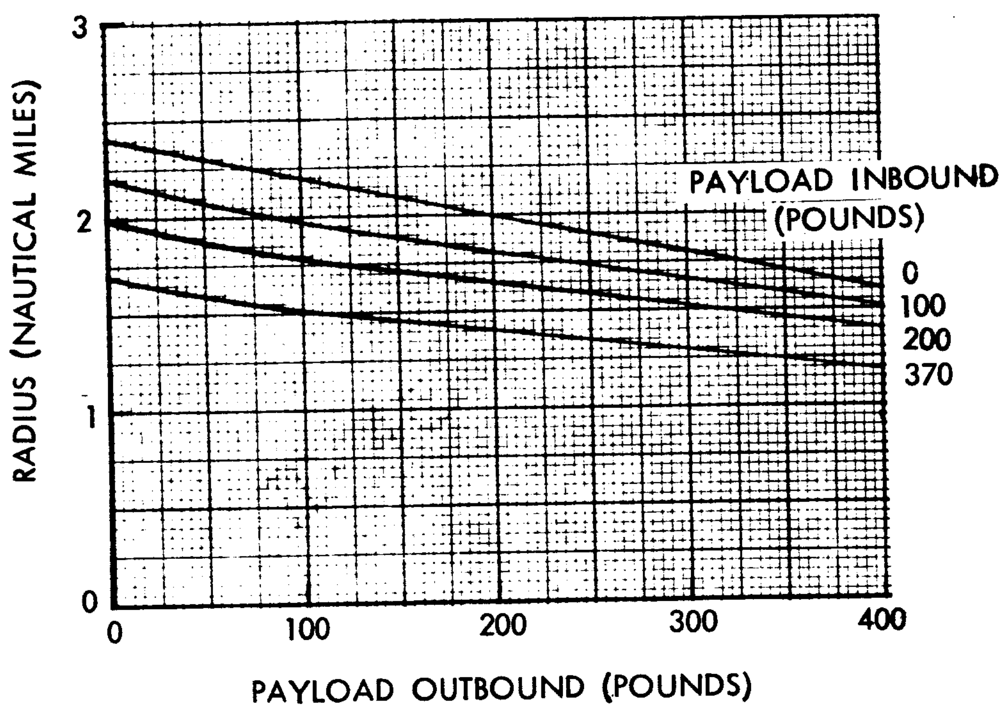


Figure 31. Constant-Altitude Trajectory Operational Radius, 150-Pound Propellant Reserve

COMPONENT	WEIGHT (POUNDS)
VEHICLE	300
PILOT	370
PROPELLANT	300
	970

RESERVES: 200 POUND PROPELLANT

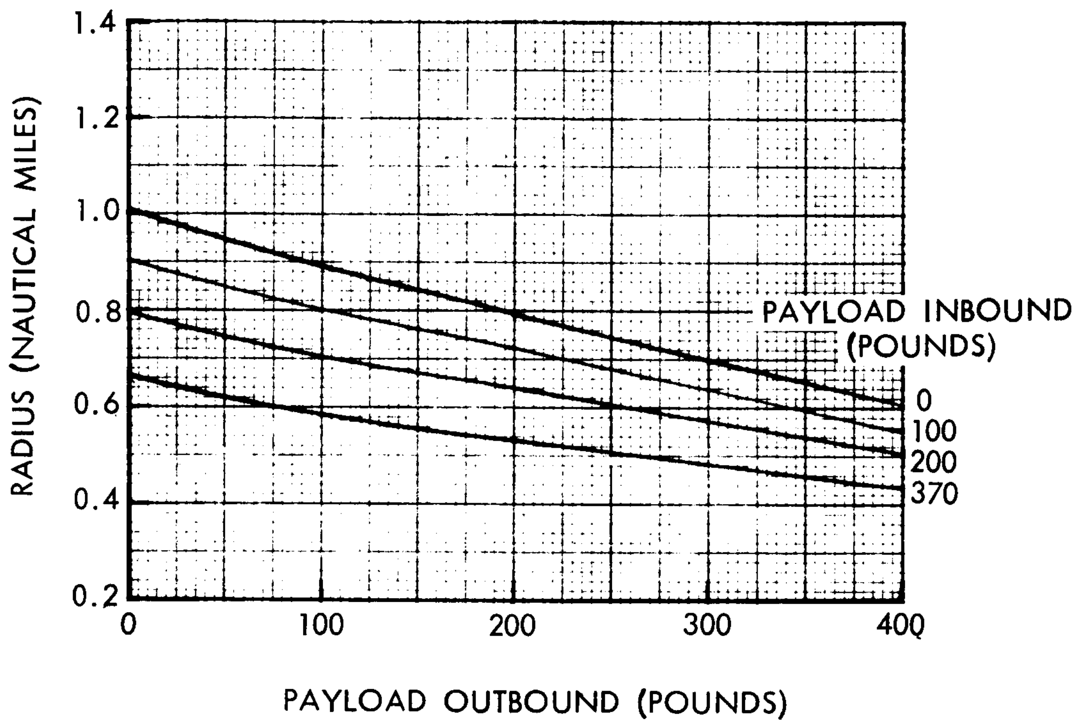


Figure 32. Constant-Altitude Trajectory Operational Radius, 200-Pound Propellant Reserve

COMPONENT	WEIGHT (POUNDS)
VEHICLE	300
PILOT	370
PROPELLANT	300
	970

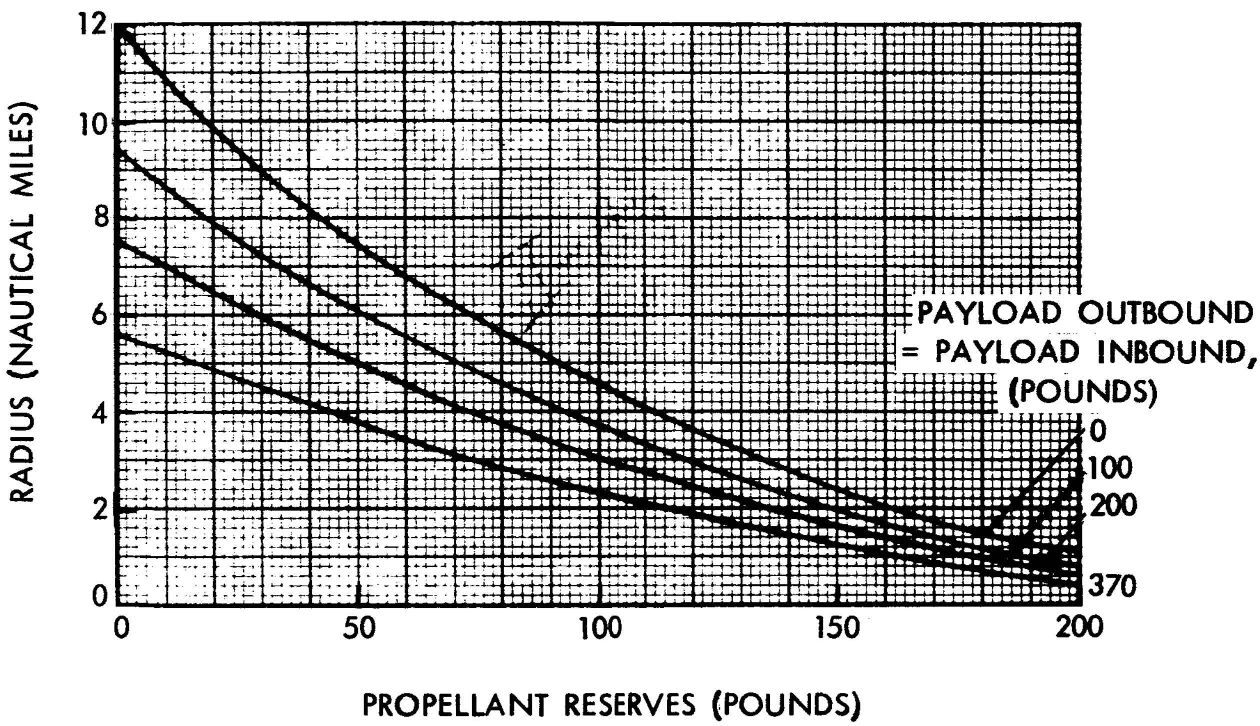


Figure 33. Effect of Propellant Reserves on Constant-Altitude Trajectory Operational Radius

To assess the most likely ranging capability of the current LFV concept, data obtained from a visual simulation (Reference 1) was employed to determine propellant requirements as a function of range when trajectory variations and landing maneuvers are included. This data is shown in Figure 34a. The pilots tended to fly a flat-top type trajectory in ascending to and descending from altitude in this simulation. The theoretical data from Figure 27 was then used to interpret the simulation results. Figure 34b presents what is believed to be the propellant requirements as a function of one-way range which are obtainable with additional training. Both the landing and trajectory variation propellants have been reduced from those experienced in simulation. The trajectory variation propellants assume that ascent to altitude is achieved by a trajectory having a ΔV midway between a flat-top and modified ballistic mode.

Figures 34c and 34d show the performance capability of the recommended concept and tradeoffs related to reductions in dry weight and in adding or removing propellant. The achievable propellant curve of Figure 34b was used in arriving at these data. Figure 34c shows the weight relationships for the current design point at 300 pounds of propellant. The eventual design goal vehicle weight is 260 pounds. Figure 34d presents the achievable radius as a function of propellant weight and inbound and outbound payload. In addition to the propellant penalties for trajectory variations and landing, this figure also includes 10 percent propellant weight for reserve and 3 percent propellant weight for residual. The current design has a maximum radius of 4.6 n mi with no payload. The design goal weight results in a 5.2 n mi radius. Increasing the propellant weight from 300 to 400 pounds increases the radius from 4.6 to 8 n mi and the vehicle dry weight increases from 300 pounds to 315 pounds. Therefore, a considerably increased radius of operation may be obtained at a moderate increase in vehicle weight.

LFV CAPABILITY WITH TWO SETS OF TANKS

To determine the maximum range capability of the recommended LFV concept, an analysis was made of the vehicle performance under the assumption that the LFV would carry (as cargo) extra helium bottles and tanks containing 300 pounds of propellant. Upon landing at the remote site, the astronaut would replace the spent helium bottles, refuel the LFV with 300 pounds of propellant from the cargo tanks, and jettison the empty containers. The dry weight of the LFV at takeoff from the LM site was assumed to consist of:

	280.0	pounds basic LFV
	65.6	pounds for extra tanks and helium bottles (full)
	16.4	pounds for 25 percent growth factor for the tanks and bottles
W_d =	362.0	pounds

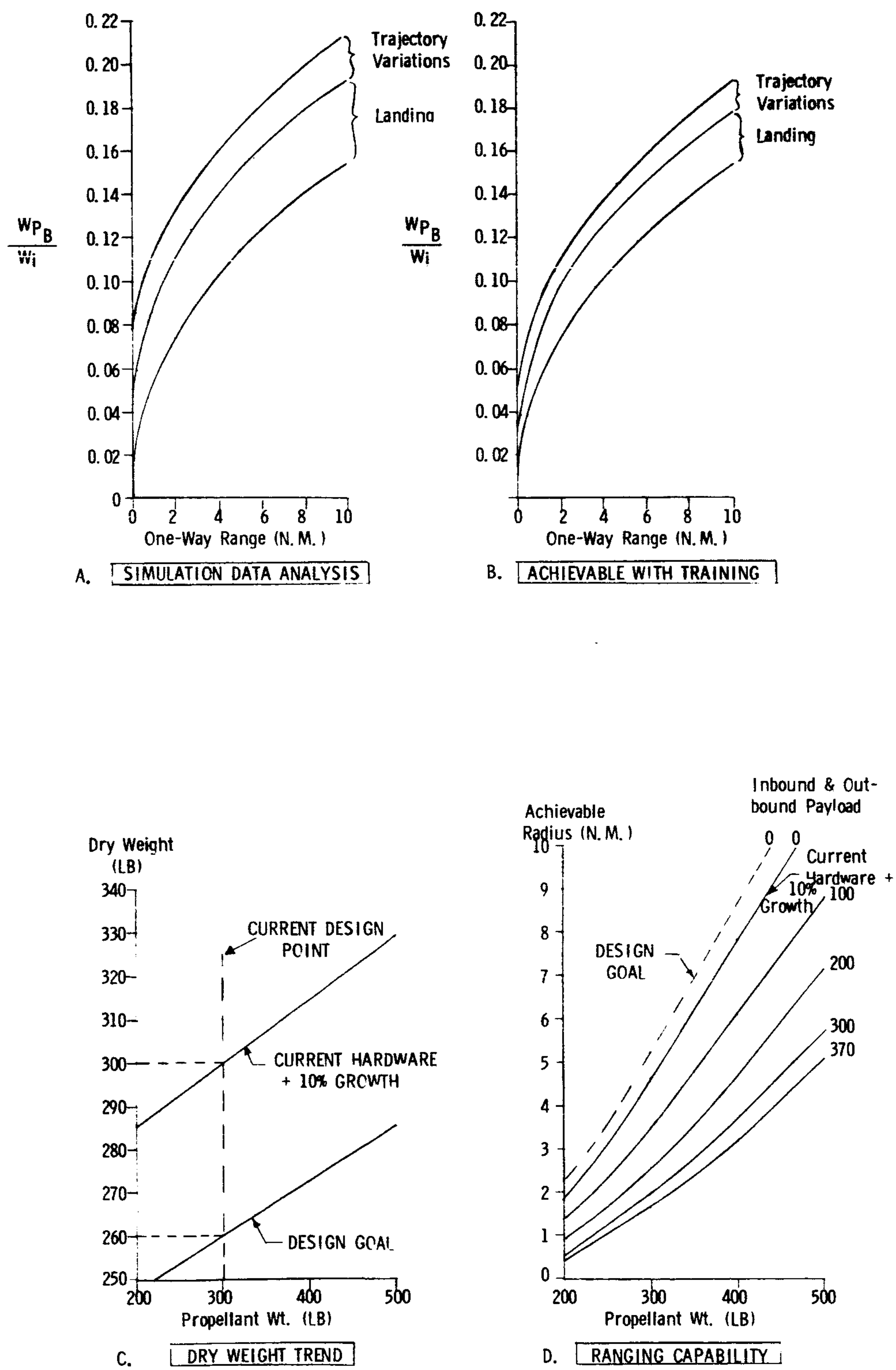


Figure 34. Achievable Ranging Capability and System Tradeoffs

Six hundred pounds of propellant would thus be carried along with a 370-pound astronaut (suited) on the outbound leg. The usable propellant weight was determined by reducing the 300 pounds by 3 percent residual and 10 percent reserve (39 pounds). This results in an outbound usable propellant-to-initial weight fraction of 0.196. Figure 34b gives an outbound range capability of 10.1 n.mi. The return flight would require less propellants because W_i would be reduced by approximately 339 pounds (300 pounds of propellants and 39 pounds of jettisoned containers).

The above calculations were repeated assuming 100 pounds and 370 pounds of payload out and back with the following results:

$$\text{100 pounds of payload:} \quad \frac{W_p \text{ outbound}}{W_i \text{ outbound}} = \frac{261}{1432} = 0.182$$

which yielded a range of approximately 8.6 n mi and,

$$\text{370 pounds of payload:} \quad \frac{W_p \text{ outbound}}{W_i \text{ outbound}} = \frac{261}{1702} = 0.153$$

which yielded a range of 5.7 n mi.

Finally, a calculation was made to determine the maximum range from which an astronaut could be rescued. It was assumed that thirty-nine pounds of containers would be jettisoned at the rescue site with the following results:

$$\frac{W_p \text{ inbound}}{W \text{ inbound}} = \frac{261}{(362-39) + 300 + 370 + 370} = \frac{261}{1362} = 0.192$$

Again, by reference to Figure 34b it is seen that rescue can be effected from a maximum range of approximately 10 n mi.

GENERATION OF TIME LINES FOR LUNAR SURFACE OPERATIONS

Time lines of lunar surface operations were generated to identify mission constraints, astronaut activities associated with the use of the LFV, and environmental characteristics prevailing during the lunar stay. By specifying assumptions where required and identifying the sequence of operations, their location, and the ambient conditions prevailing, problem areas were identified which could then be attacked and resolved.

A post-Apollo, three-day Extended lunar module (ELM) stay time was used for the nominal mission. Dawn landing at a 10-degree sun angle was assumed. The time lines, while commencing at touchdown, assumed that the astronauts' day began upon awaking six hours before LM touchdown. Consequently, the initial sleep period is shown as occurring 9.5 hours after touchdown.

To span the range of possible LFV sorties, three types of excursions were examined: a half-mile qualification flight (for each astronaut), a maximum-range sortie, and a triangular (equiliateral) mission during which two sites were visited. Also, the capability of the LFV to fly to the top of an 8000-foot peak was verified. Detailed site tasks not bearing on the LFV were not generated because they were considered not germane to the determination of the capability, flexibility, or feasibility of the man-LFV system. The three types of sorties provide an envelope within which lie the LFV mobility requirements identified by the scientists (i.e., long range, short range, multiple stops, mountain peaks). A detailed analysis of a hypothetical mission was not made because it was not considered to be sufficiently meaningful to the LFV design or evaluation to warrant the expenditure of the man-hours that would be required. A study (Reference 2) of lunar sites of scientific interest and the mobility requirements for their investigation revealed that substantial scientific benefits could be attained with an LFV with a 5-km-radius capability. The time lines generated did, however, include all sortie activities that pertained to the LFV.

The scope of the effort was limited to the generation of six time lines:

Two LFV's	One LFV
1. Nominal three-day lunar dawn mission	1. Nominal three-day lunar dawn mission
2. Three-day sunset mission	2. Three-day sunset mission
3. 14-day daylight mission	
4. An LFV rescue mission	

A time line was not generated for the 14-day mission with only one LFV because such a mission would undoubtedly include the use of a surface roving vehicle, and the LFV operations would be closely integrated with those of the roving vehicle. The incremental LFV information to be obtained from such a time line was not considered to justify the generation and analysis of highly speculative assumptions regarding such operations. The time line of the 14-day daylight mission with two LFV's was considered adequate for demonstrating the operational mode of the LFV during extended staytime. Since the initial use of the LFV is scheduled for the ELM mission, which is currently planned as a three-day lunar dawn mission, it was construed to be the nominal or base-line mission.

METHOD OF APPROACH

Key assumptions and constraints associated with system characteristics in the post-Apollo period that had a bearing on the ELM/LFV missions were defined. Once the constraints and assumptions were specified, the major mission operations were identified. In reviewing these operations, several potential problem areas were uncovered. Through analyses in these areas, the preferred alternative operating modes were identified and incorporated into the time lines. Admittedly, judgment had to be used extensively, particularly in determining activities and times associated with the 14-day mission, which is beyond the capability of current systems.

ASSUMPTIONS AND CONSTRAINTS

Every mission was based on a set of assumptions and constraints. Lunar landings for the dawn and daylight missions were assumed to occur at a sun angle of 10 degrees, a favorable lighting condition. This reflects the operational requirements and conclusions reached in several basic planning documents (References 3 and 4) with respect to sun angle at landing. A lunar near-equatorial region (± 15 degrees latitude) was assumed as the landing site for the dawn and daylight missions to impose the most severe thermal environment. Three- and 14-day lunar surface staytimes were assumed. In the first four mission time lines, two LFV's and an advanced Apollo lunar surface experiment package (ALSEP) were assumed to be landed by the two-man ELM. In the remaining two cases (no rescue) only one LFV was assumed to be carried by the ELM. Eleven hours of personal maintenance and rest per day were assumed. This was generally divided into one 8-hour sleep period and three 1-hour periods for eating, personal grooming, rest, etc. In all three-day missions, 1000 pounds of recoverable propellant were assumed to remain in the LM descent stage for use in the LFV's. It was recognized that significant spacesuit improvements will probably be made over the next several years while the LFV is being developed. Consequently, the A-7L suit with a 25 percent mobility improvement was assumed to be used.

For the three-day lunar sunset mission time lines, the assumption was made that the maximum permissible sun angle (20 degrees) prevailed upon landing to permit maximum use of sunlight before nightfall. A typical location for this mission would be in the Marius Hills region (14°N, 56°W) so that almost full earthshine would be available for night-time operations.

In the case of the 14-day missions, it was assumed that a lunar logistics cargo vehicle (LCV) was landed before the ELM mission, 0.5 n.m. from where the ELM set down. The LCV was assumed to contain a shelter and a 1000-pound propellant payload in addition to the 1000 pounds available in the two-man ELM descent stage. The third astronaut was assumed to remain in lunar orbit in the CSM during the 14-day surface stay. Excursions with the LFV were limited to periods before and after lunar noon, during which the sun elevation was less than 45 degrees. This constraint was based on the increased thermal load and on the anticipated difficulty of LFV navigation at high sun angles which wash out the contrast of lunar features, making them hard to discern. (Apollo 10 astronauts experienced difficulty in observing lunar landmarks through the sextant at high sun angles.) However, an alternative operational mode which did not include this constraint was considered and is indicated in the time-line data.

The rescue-mission time line assumed that the need for rescue arose just before departure from a remote site, to verify the ability to rescue astronauts before their PLSS was exhausted.

In the missions with only one LFV (no rescue capability), it was assumed that both scientist/astronauts would make sorties on it.

All of the time lines assumed that the first flights of the LFV's would be qualification-familiarization flights. Although extensive training in flying the LFV's would have been given the scientist/astronauts, a test flight within walk-back range was considered to be prudent from both psychological and technical viewpoints.

RESULTS AND CONCLUSIONS

The six time lines generated during this task are presented in the appendix, which includes:

1. A nominal three-day dawn mission with two LFV's
2. A three-day sunset mission with two LFV's
3. A 14-day daylight mission with two LFV's
4. An LFV rescue on any of the above missions.
5. A nominal three-day dawn mission with only one LFV available, and hence no rescue capability.
6. A three-day sunset mission with one LFV.

Figure 35 shows the relationship between lunar surface staytime and number of LFV sorties. Tables 4 and 5 show the propellant consumption schedule for the nominal three-day and for the 14-day missions with two LFV's. It is significant that on a 14-day mission the maximum amount of propellant that can be productively consumed by the two LFV's as currently conceived is approximately 5750 pounds. Figure 36 shows the sun angles and surface temperatures to be encountered on each of the five LFV flights for the nominal three-day dawn mission with one LFV. Figure 37 shows the relative productivity of the rescue and no-rescue modes for the three-day mission. Without the requirement for rescue, all three LFV sorties can be made to maximum range. The no-rescue mode was considered to make the qualification flights even more essential. During the three-day maximum staytime with one LFV it is necessary that the scientist/astronauts alternate in conducting the LFV sorties; otherwise, one of them will have to perform sorties at a rate of two per day. At present this is considered to be too exhausting.

The time lines indicated that three-day lunar missions using the LFV for surface mobility are feasible and strike a good balance among the amount of residual propellant expected to remain in the ELM descent stage, the mission duration, the capability of the spacesuited scientist/astronaut, and the attainment of highly desirable scientific data through access to remote locations of high scientific interest.

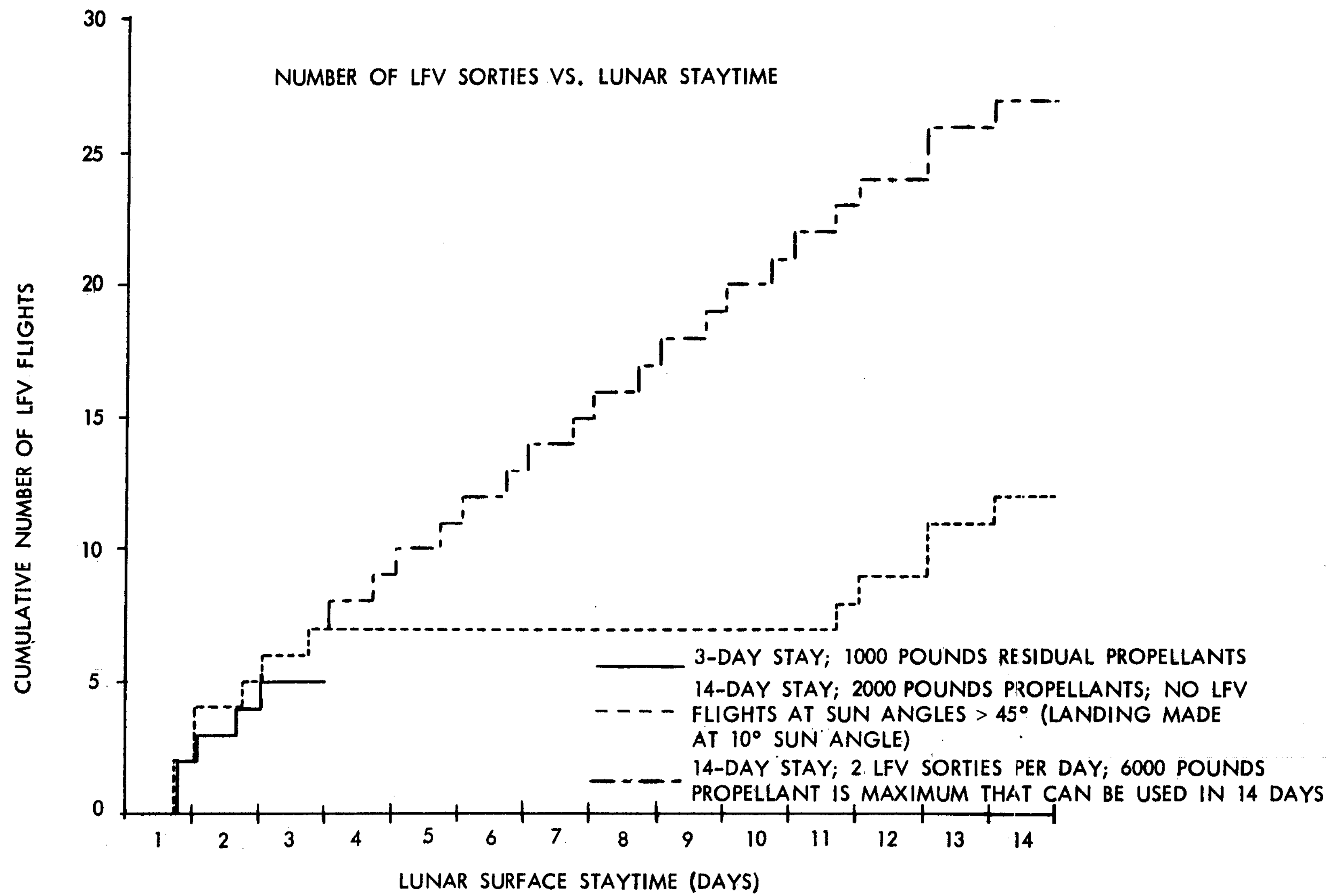


Figure 35. Number of LFV Sorties Versus Lunar Stay Time

Table 4. Propellant Usage - 3-Day Mission

EXCURSION	Quantity in Tanks Before Flight (pounds)		Quantity Consumed During Flight (pounds)		Quantity Refueled From ELM (pounds)	Balance After Refueling (pounds)
	LFV-1	LFV-2	LFV-1	LFV-2		
Initial Fueling	0	0	0	0	650	350
1 EVA 3 LFV-1	300	300	100		100	250
2 EVA 4 LFV-2	300	300	100		100	150
3 EVA 5 LFV-2	300	300		250	150	0
4 EVA 6 LFV-1	300	200	270*			
5 EVA 7 LFV-2	30	200		170		
	30	30	470	420	1000	

* Triangular Flight

RECAPITULATION:

Consumed During Flight

LFV-1	470 pounds	
LFV-2	420	
	890	890
Balance Remaining		
LFV Tanks (reserve)	60	
Residuals	50	
	110	110
		1000

Table 5. Propellant Usage - 14-Day Mission

EXCURSION	Quantity in Tanks Before Flight (pounds)		Quantity Consumed During Flight (pounds)		Quantity Refueled From		Balance After Refueling (pounds)	
	LFV-1	LFV-2	LFV-1	LFV-2	ELM	LCV	ELM	LCV
Initial Fueling	0	0	0	0	650		350	1000
1 EVA 3 LFV-1	300	300	100		100		250	
2 EVA 4 LFV-2	300	300		100	100		150	
3 EVA 5 LFV-1	300	300	50			50		950
4 EVA 6 LFV-2	300	300		50		50		900
5 EVA 7 LFV-1	300	300	200			200		700
6 EVA 8 LFV-2	300	300		250		250		450
7 EVA 9 LFV-1*	300	300	200			200		250
8 EVA 28 LFV-1	300	300	250			250		0
9 EVA 29 LFV-2	300	300						
10 EVA 30 LFV-1	300	100	50	200				
11 EVA 31 LFV-2	250	100	50		150		0	
	250	200	850	650	1000	1000		
RECAPITULATION:								
Consumed During Flights								
LFV-1				850				
LFV-2				650				
				1500	1500			
Balance Remaining								
LFV-1				250		Miscellaneous Flight EVA 33		250
LFV-2				200	450	Emergency reserve		200
				450				450
Residuals								
LFV-1				25				
LFV-2				25	50			
				50	2000			

*Fifteen additional LFV excursions can be performed at a rate of two/day if sufficient propellant is carried on LV (15 x 250 = 3750 pounds more) and if high sun illumination is not found to be detrimental to navigation during 7-1/2-day period bracketing lunar noon.

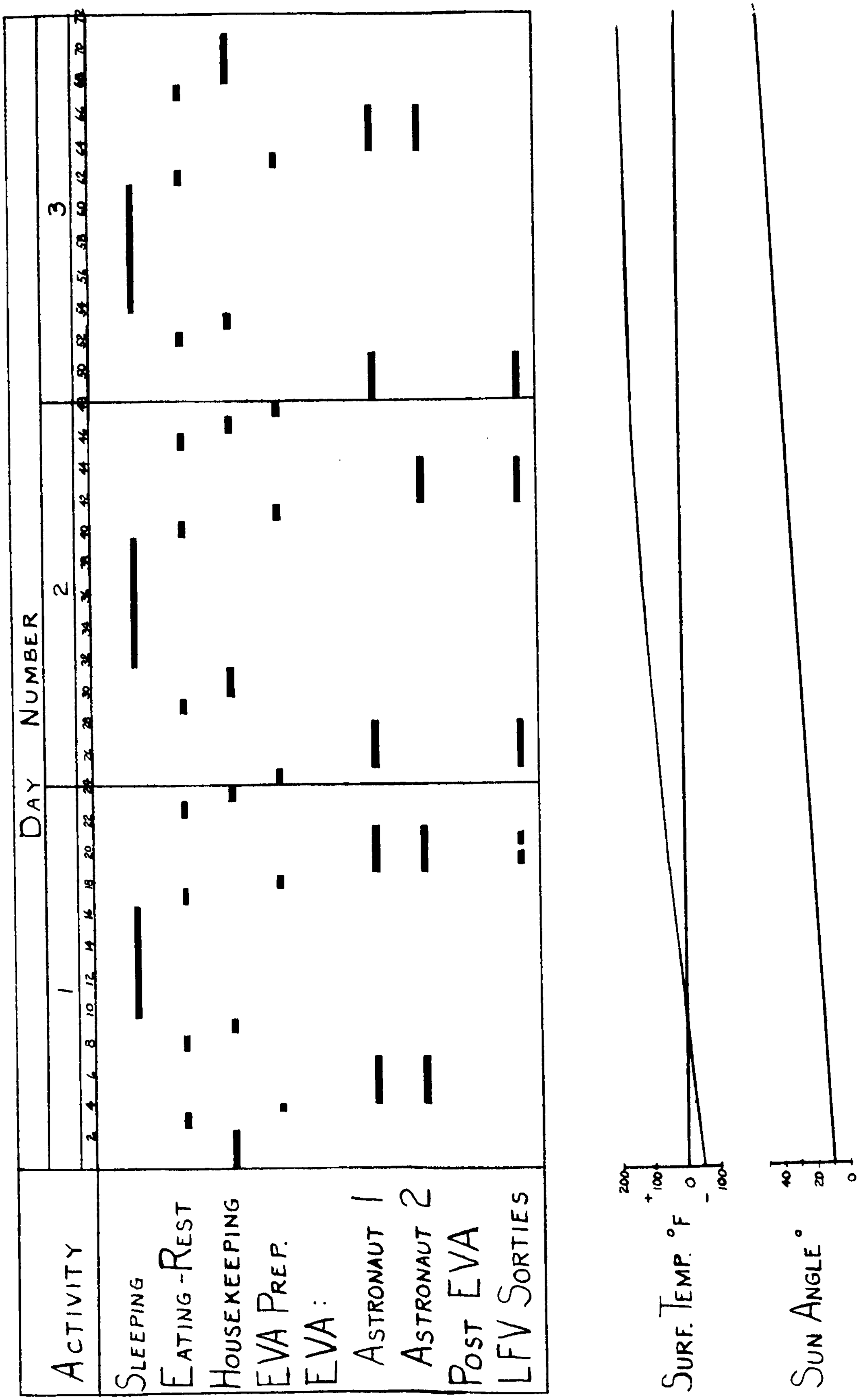
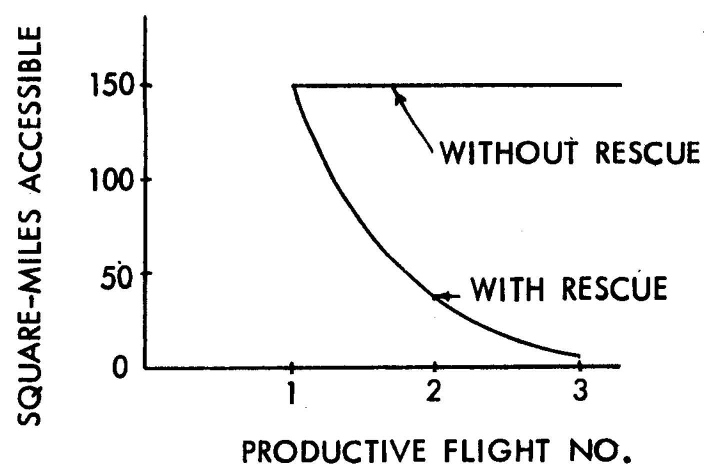


Figure 36. Nominal Three-Day Dawn-Mission Timeline for One LFV



FLIGHT	RANGE (NM) 2 LFV'S	1 LFV
1	0.5	0.5
2	0.5	0.5
3	7.0	7.0
4	3.5	3.5
5	0.5	7.0

Figure 37. Comparison of Rescue and No-Rescue Modes

The basic 14-day daylight mission time line limited the use of the LFV's to periods during which the sun angle was less than 45 degrees. A near-equatorial landing site (± 15 degrees) was assumed. If a higher-latitude mission (say, 45 degrees) was undertaken, this restriction would not apply and LFV flights could be made throughout the 14-day period. The restriction was based on the increased thermal load that would be placed on the space-suit at high lunar surface temperatures and on the potential LFV navigation problem due to washout of surface features when flying at several hundred feet at high sun angles. Since a deep lunar core sample (100 to 300 meters) is one of the desires of scientists, the "noon" period could be used for this activity.

SOIL EROSION STUDIES

PLUME - INDUCED PROBLEM AREAS

Upon launch or landing of the LFV, the rocket engines produce a thrust on the order of 130 to 190 pounds. The ejecta produced by the impingement of the rocket engine exhaust upon lunar soil is potentially hazardous. This task was undertaken to investigate the extent and severity of the potential hazards. Questions pursued included:

1. What is the effect of the plume-disturbed soil on visibility?

2. Does the eroded soil present a hazard to the LFV and/or astronaut through contamination, erosion, physical impact, or in other ways?

3. Can the eroded soil particles present a hazard to equipment deployed nearby? Is there a possibility of ELM ascent stage penetration?

4. What steps can be taken to alleviate the potential hazards?

The above questions are answered in this and in the following sections.

ANALYSIS OF CHARACTERISTICS OF LUNAR SOIL EJECTED BY ROCKET PLUME IMPINGEMENT

Rocket engine plume impingement on soil is a poorly understood phenomenon. The German Dornier Company has mounted a jet engine on an articulated frame on the back of a truck to run tests on the soil erosion effects encountered in the use of heavy VTOL aircraft (Reference 5). The lack of understanding is further compounded by uncertainty with respect to lunar soil characteristics. Among the sources of data examined during the study were:

1. Technical Report 32-1246 Surveyor V Mission Report, Part II: Science Results. Jet Propulsion Laboratory, 1 November 1967

2. NASA SP-166, Surveyor VI, A Preliminary Report, March 1968

3. Technical Report 32-1264 Surveyor VII Mission Report, Part II: Science Results. Jet Propulsion Laboratory, 15 March 1968.

However, some of the most significant data were obtained from test firings of a Surveyor vernier engine into simulated lunar soil in the Langley 41-foot vacuum chamber. Elmer M. Christensen of JPL obtained these data in the course of his NASA funded study: Lunar Surface and Soil Erosion/Adhesion Studies. High speed movies of the Langley test firings into simulated lunar soil indicated that neither the exhaust plume nor the eroded lunar soil would interfere significantly with surface visibility. The Langley results and Surveyor data were combined with theoretical erosion models to develop relationships which describe the effects anticipated from the LFV engines.

Figure 38 shows the resulting relationship between particle size and maximum particle velocity in the lunar environment during landing and lift-off. The uppermost curve shows that a particle 1 cm in diameter (with a specific gravity of 2.4) could be accelerated by the exhaust gases upon lift-off to a velocity of 21 fps. Figure 39 shows the maximum distance of travel of ejecta under lunar conditions as a function of particle size for landing and liftoff.

An analysis of the crater left after test 41-062 (at the Langley vacuum chamber previously mentioned) in which a Surveyor vernier engine (5.1 inches nozzle exit diameter) was fired at 30 pounds of thrust for 10.1 seconds while descending from 17 feet down to 5 feet above a simulated lunar soil (consisting of particles ranging from 1μ to 700μ with average size of 62μ) revealed that ejecta was thrown at an angle of approximately 30 degrees. Figure 40 shows an idealized profile of the crater which was produced as a result of the test firing. Analysis of other test firings indicated that descent to closer than 5 feet (nozzle height) or lengthy hovering at low heights could produce ejecta at higher angles.

A number of the test results gave evidence of diffused gas eruption upon engine shutdown at low nozzle height. This phenomena could result in deposition of lunar soil in the nozzle and on unprotected control mechanism, with possible degradation of reliability.

To determine the hazard presented by particles 1 cm in diameter traveling at approximately 20 fps, calculations were made of the penetrating capability of such particles. Two different emperical equations were used to allow a comparison:

$$P = \frac{1.38\, d_p^{1.1}\, \rho_p^{1/2}\, V_p^{2/3}}{H_t^{1/4}\, \rho_t^{1/6}} \quad \text{(1) North American Rockwell}$$

Space Division
North American Rockwell

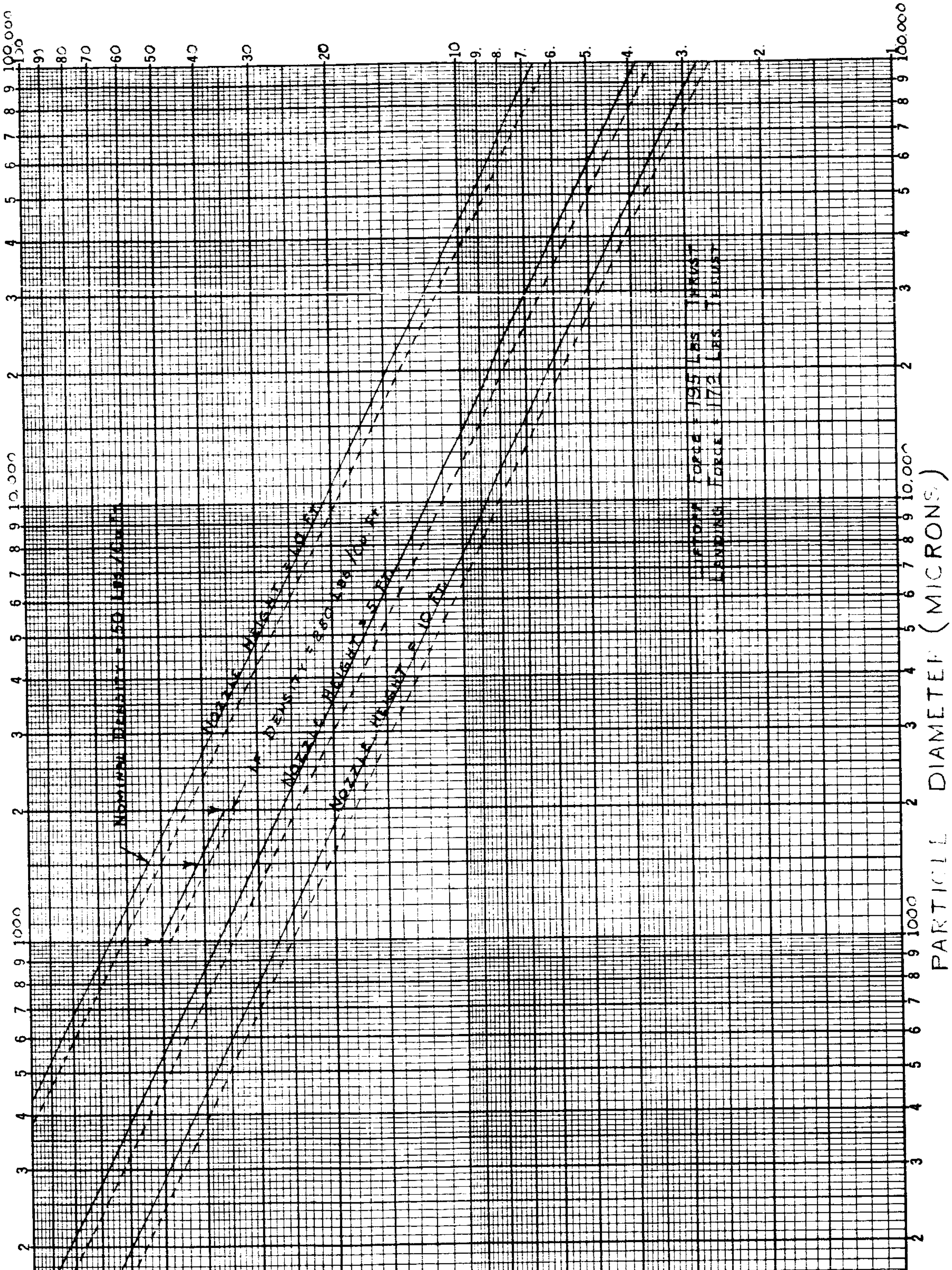


Figure 38. Maximum Particle Velocity Versus Particle Diameter
(Sheet 1 of 2)

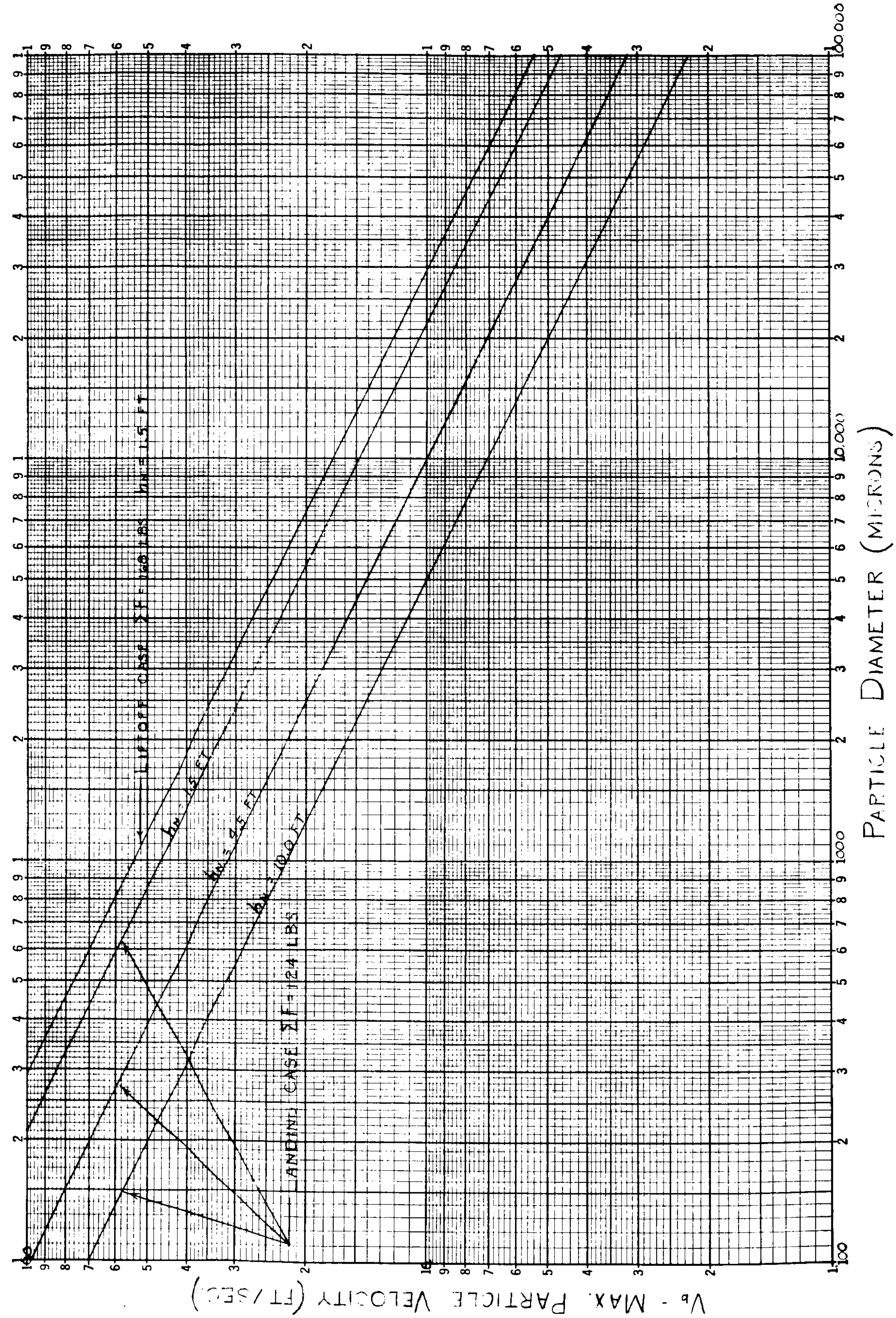


Figure 38. Maximum Particle Velocity Versus Particle Diameter
(Sheet 2 of 2)

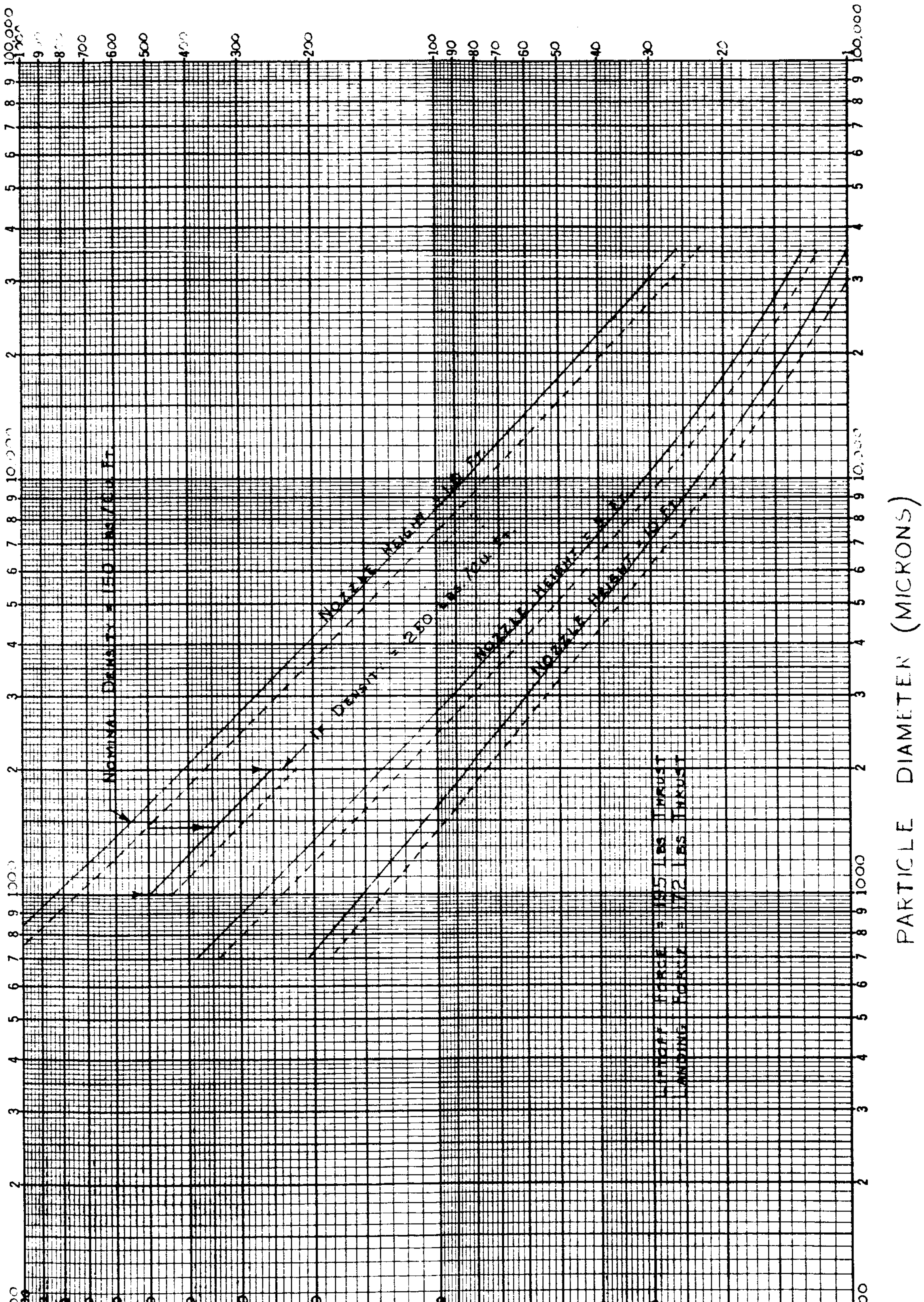


Figure 39. Ejecta Travel Versus Particle Diameter (Sheet 1 of 2)

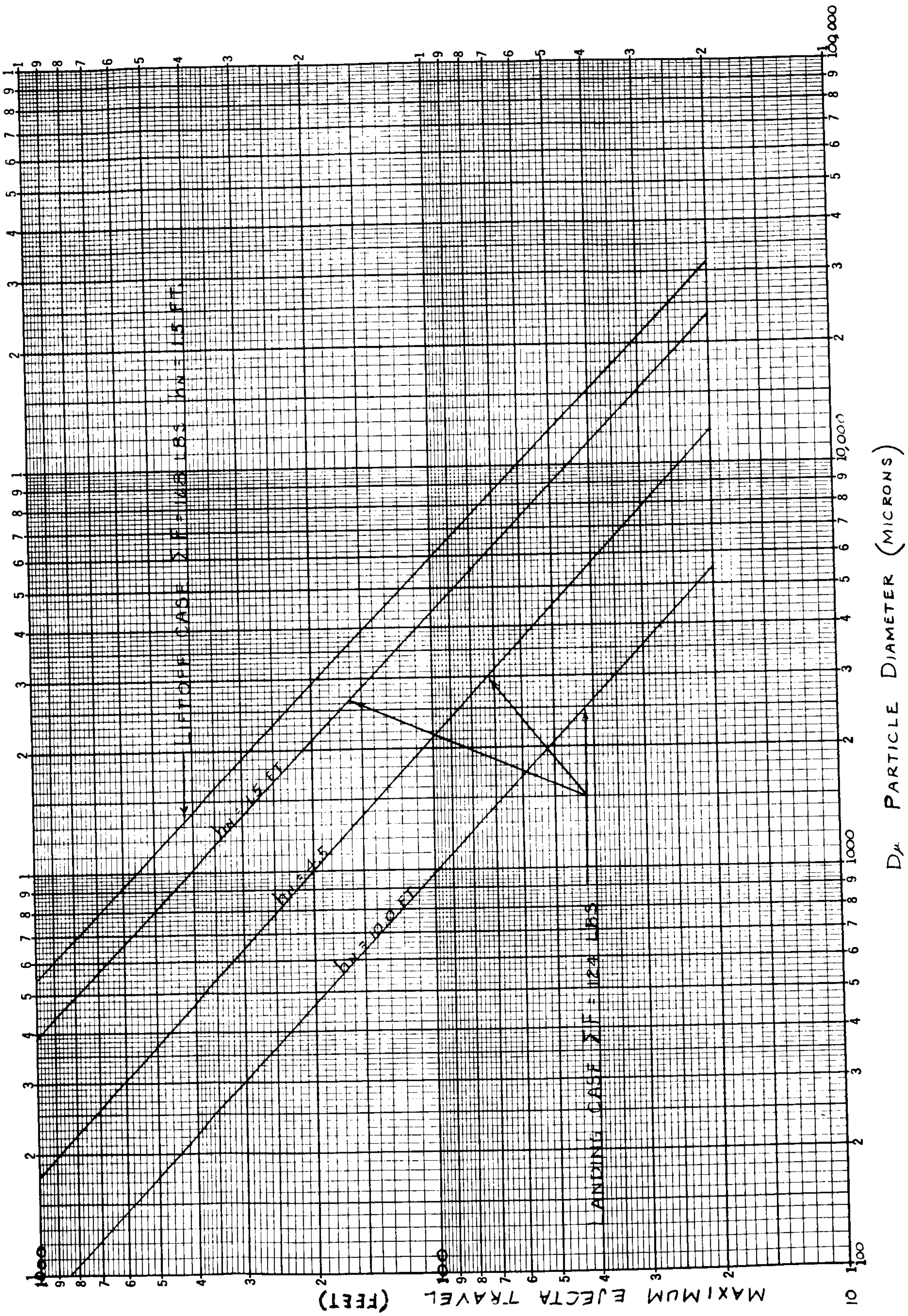


Figure 39. Ejecta Travel Versus Particle Diameter (Sheet 2 of 2)

TEST : 41-062
FIRING TIME : 10.1 SEC.
THRUST : 30 LBS
NOZZLE HEIGHT : 17 FT. TO 5 FT
INITIAL AMBIENT PRESSURE : 0.070 MM HG
FINAL AMBIENT PRESSURE : 0.60 MM HG
PARTICLE SIZE : 1μ TO 700μ, AVE. 62μ
VOLUME ERODED : 0.25 CU. FT.
WEIGHT OF SOIL ERODED : 27 LBS

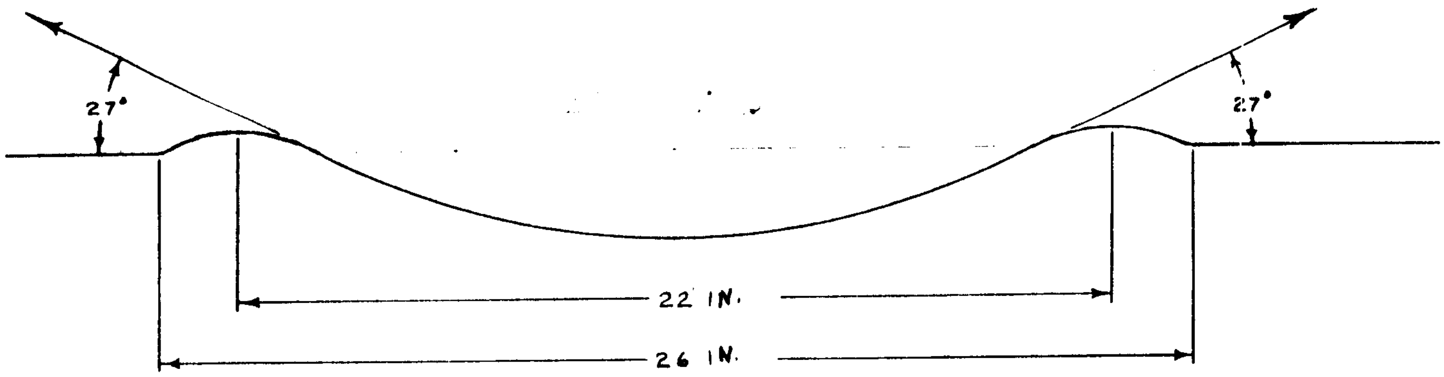


Figure 40. Cross-Section of Crater Produced in Simulated Lunar Soil Under Vacuum Conditions During Test Firing of Descending Rocket Engine

where

P = penetration in cm

d_p = diameter of particle in cm

ρ_p = density of particle in grams/cm^3

V_p = velocity of particle in km/sec

H_t = Brinell hardness no. in kg/mm^2

ρ_t = density of target in grams/cm^3

and

$$D = 2.78\, d \left(\frac{\rho_m}{\rho_t}\right)^{2/3} \left(\frac{V_m}{V_t}\right)^{2/3}$$ (2) TRW Space Data 3rd Edition, page 30

where

D = depth of penetration in cm

d = diameter of particle in cm

ρ_m = density of particle in grams/cm^3

ρ_t = density of target in grams/cm^3

V_m = velocity of particle in ft/sec

V_t = speed of sound in target material in ft/sec

Upon solving the two penetration equations for a particle 1 cm in diameter with a specific gravity of 3.0 traveling at 20 fps and striking an aluminum target, it was found that one equation gave a value of 0.22 mm for the depth of penetration, while the other gave 0.34 mm. The mean of these values is 0.28 mm. The skin of the LM ascent stage is 0.01 inches thick, or 0.25 mm. Consequently, there is a good possibility that a 1 cm diameter particle accelerated to a velocity of 20 fps and striking the ELM could penetrate the skin. Because the exhaust of the LFV rocket engines could accelerate particles to approximately this velocity, the use of launch and landing pads in the vicinity of the ELM and the deployment of launch cloths at remote sites was studied. (See Section on Deployment of LFV).

CONCLUSIONS

Preliminary analysis of the data obtained by E. M. Christensen (Reference 6) indicates that at 16 pounds of thrust, 14.6 inches nozzle height, 0.1 mm Hg vacuum, and 0.5 seconds firing time, a 2-1/2 gram particle was observed to be accelerated to a velocity of approximately 10 feet per second; at 30 pounds of thrust and under similar test conditions, an 86-1/2 gram particle was observed to be accelerated to a velocity of approximately 5 feet per second. The 41-062 test previously mentioned produced ejecta at approximately a 30-degree angle when the nozzle was 5 feet above the surface. By flying down lower, the ejecta produced could impinge on the LFV with detrimental results. Furthermore, diffused gas eruptions were observed upon engine shutdown in some of the Langley tests. This phenomenon could throw lunar soil into the nozzles and on unprotected control mechanism. Consequently, upon landing at a remote site, an engine cutoff at a height of 50 inches (nozzle to ground) was assumed as a normal operational procedure, because at this height the ejecta from the crater should not impinge on the LFV.

Because the exhaust of the LFV could accelerate particles to a velocity sufficient to penetrate the skin of the LM ascent stage, the use of launch and landing pads is recommended for LFV operations in the vicinity of ELM. Similarly an expendable ground cloth was assumed to be deployed under the LFV prior to launch from a remote site. The purpose of the cloth is to prevent ejecta during takeoffs. See the GSE and LSE Studies section of this volume for a discussion of ejecta range, LFV deployment distance, and ground cloth material.

GSE AND LSE STUDIES

The GSE and LSE studies encompassed those areas of lunar activities and systems that had a bearing on the safe and efficient deployment and use of the LFV. Included in the studies was a brief investigation of the feasibility of an astronaut dismounting the LFV from the ELM and assembling and deploying it while in a spacesuit. Another problem studied was the determination of the distance between the ELM and LFV for safe operations. Data from the soil erosion study was used to establish the need for use of a launch/landing pad for the LFV, as well as the use of launch cloths on sorties. To provide a check list for ancillary equipment and operations required for efficient and qualification and use of the LFV, a preliminary functional analysis was performed. Finally, preliminary GSE and LSE specifications were generated. Each of these activities will be discussed in the following sections.

ASTRONAUT SPACESUIT CAPABILITIES

It was recognized that during development and production of the LFV spacesuit designs will continue to improve to permit greater astronaut mobility and dexterity. The assumption was made that the mobility capability of the A-7L spacesuit would improve by 25 percent. To verify the capability of the astronaut to mount and dismount from the LFV while in a spacesuit. and to obtain more realistic timelines, various activities were performed using a full-scale mockup of the LFV and a test subject garbed in a pressurized spacesuit (A-5L). It was found that while both the dismounting and assembly of the LFV, if necessary, could be performed by one astronaut without any major modifications to the ELM. However, normal operations would have the two astronauts working together.

DEPLOYMENT OF THE LFV

Data from the Surveyor missions (Reference 7) indicate that particles in the size range between 0.8 cm and 1.6 cm are very common on the lunar surface. Table 6 summarizes the Surveyor mission data.

Included in Table 6 are the average number of particles that could be expected in the flat surface area of a crater such as that produced in JPL test 41-062 shown in Figure 40. These data indicate that a significantly large number of particles of the size mentioned can be expected to exist in

Table 6. Average Prevalance of Fragments in the 0.8 to 1.6 cm Diameter Range on the Lunar Surface

Mission	Average Number of Particles/sq ft	Average Number of Particles in Area of Test 41-062 Crater
Surveyor I	4.2	7.4
Surveyor VI	7.4	13.0
Surveyor VII	12.5	22.1
Mean:	8.0	

the rocket plume impingement area. The significance of the 0.8 to 1.6 cm size range may be ascertained from Figure 41 which shows the hazard posed by soil ejecta in terms of LM penetration capability. As the size of particles of a given density increases, their maximum range (for a given exhaust plume condition) decreases. Particles smaller than 0.8 cm while having substantial range (velocity) do not possess sufficient penetration capability. On the other hand, particles larger than 1.6 cm have maximum ranges less than approximately 40 feet.

Figure 41 shows that a particle of a given size can be accelerated by the rocket exhaust upon landing or liftoff to a velocity which will give it the maximum range (at a 45-degree angle) shown. This same velocity is sufficient to give the particle(s) the depth of penetration indicated by the ordinate value. Without some type of ejecta-preventing or deflecting device, the liftoff curve in Figure 41 indicates that the LFV would need to be launched more than 80 feet from the ELM to eliminate the possibility of penetrating the ascent stage. This was considered an undesirable distance, as will be shown in the section on refueling modes. Among the types of protective devices considered were ejecta deflectors (shields), soil stabilizers/solidifiers, and a cloth launch/landing pad (blanket). The deflectors were considered undesirable because they would need to extend above the lunar surface for several feet, thus presenting a hazard in themselves or from ricocheting ejecta; they would need to be fairly strong and rigid, and thus relatively heavy; and finally, they would need to be located between the LFV and the ELM and would present an obstacle the astronauts would need to walk around in going between the ELM and LFV. An analysis of the comparative merits of soil stabilizers and launch/landing pad materials indicated that the launch/landing pads appeared preferable on the basis of weight, reliability of protection, development time and cost, and deployment time. The deployment of the launch/landing pads was included in the timelines.

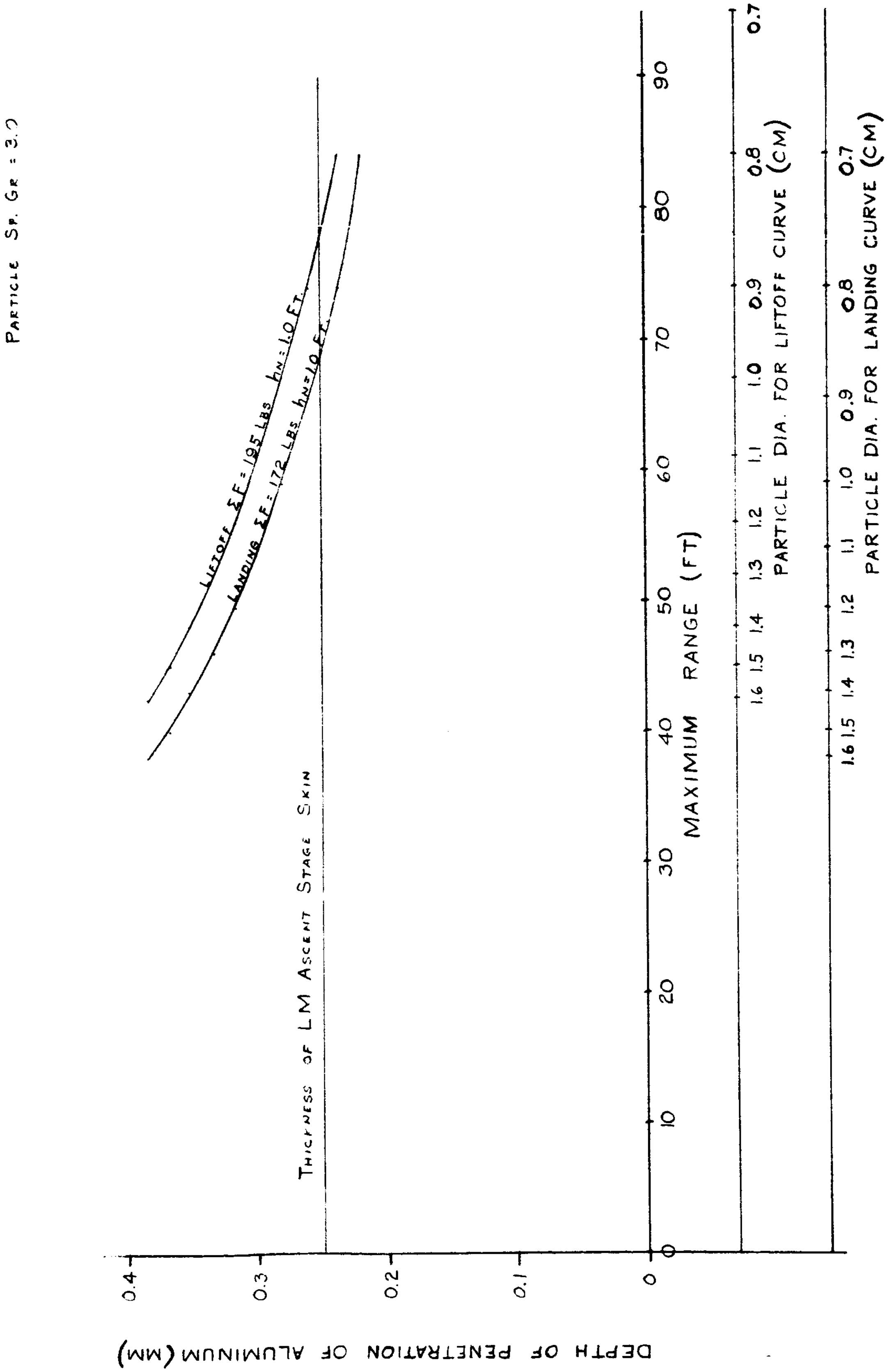


Figure 41. Typical Penetration Capability of Lunar Particles Accelerated by LFV Exhaust Plume

Because the landing astronaut could not see the launch/landing pad when hovering over it and descending down onto it, landing aids would be deployed adjacent to the pads. One concept would use four strips of temperature resistant cloth that are laid and staked down (before the launch/landing pad is deployed) and that intersect under the center of the launch/landing pad.

A safe operational distance between the ELM and LFV launch/landing pad was determined to be approximately 40 feet. This distance was arrived at by considering the effect of a control anomaly upon liftoff (e.g., weight imbalance, engine failure, etc.) which might cause the LFV to veer off the launch/landing pad at a few feet altitude before setting down. The JPL tests at Langley revealed that the eroded craters tend initially to have relatively shallow slopes. It was considered unlikely that an anomalous control situation would cause a crater to be dug with slopes significantly greater than approximately 30 degrees. If the maximum range curves for particles which were based on a 45-degree ejection angle were adjusted for a 30-degree ejection angle, then particles ejected at 20 fps at a 30-degree angle 40 feet away from the ELM would not impinge on the ascent stage. If it is assumed that the potentially hazardous-sized particles are ejected at a random heading, then the probability that any one would head towards the ELM is approximately 0.05 if the separation distance is 40 feet. A particle ejected by a control anomaly situation would have to be of the right size, with the right velocity at the right heading, and ejected at an elevation angle greater than 30 degrees to penetrate the LM ascent stage. Consequently, the 40-foot distance between the ELM and LFV launch/landing pad was considered to be a reasonable distance for safe operations.

LFV REFUELING MODE

Another area investigated was the question of whether provisions should be made for moving the LFV closer to the ELM for refueling, or whether hoses should be deployed to the LFV on its launch/landing pad. Incremental weight was the key criterion applied in this analysis. An assumption was made that the refueling operations should be performed within easy view of the operation-monitoring astronaut within the ELM. A review of LM data indicated that to be easily observable, the refueling should be done at a minimum distance of approximately 15 feet from the ELM. Consequently, if hoses are to be used, separate fuel and oxidizer hoses would need to be approximately 50 feet long to include the distance from the ELM fittings to the ground, a 40-foot distance, and again from the ground to the LFV tank fittings. Similarly, 25-foot hose lengths would be required to refuel at 15 feet. Figure 42 summarizes the analysis which led to the resolution of refueling mode. The combined weight of the two hoses was estimated to be approximately

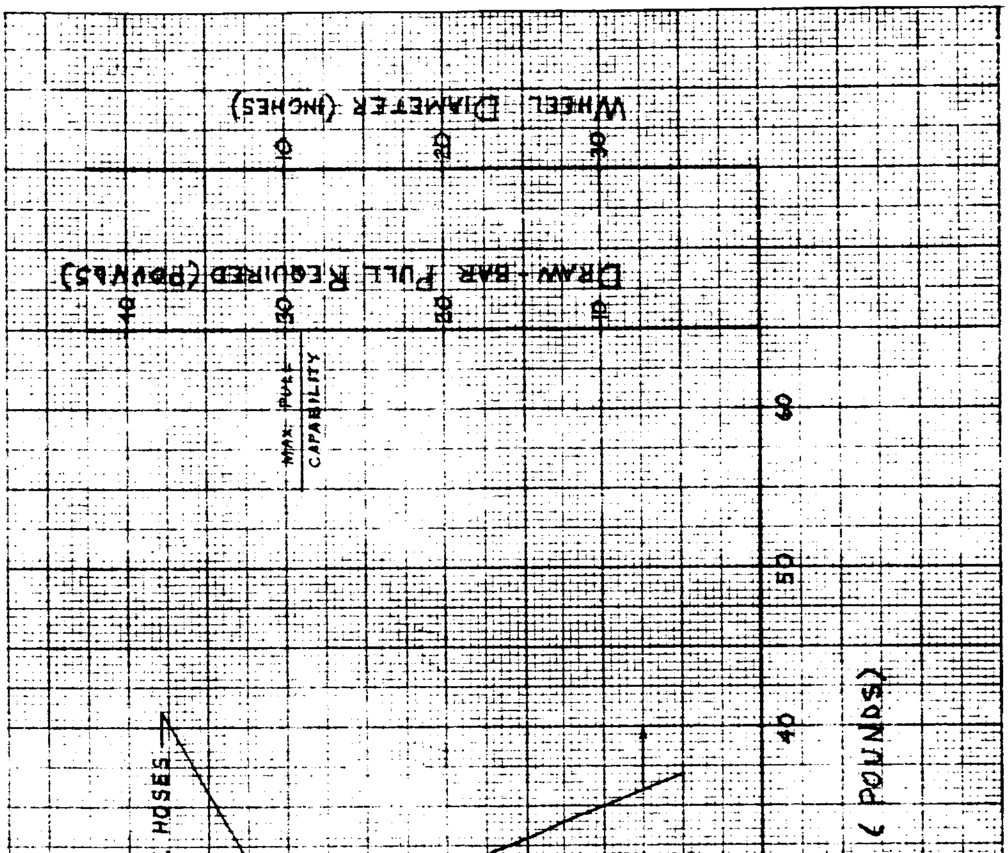


Figure 42. Hoses Versus Wheels Tradeoff

0.2 pounds per foot, with an estimated total weight of five pounds for the four fittings on the ends of the hoses. The hose length versus weight curve shows this relationship. The minimum safe LFV launch/landing pad distance of 40 feet would require 50 feet of hoses. The minimum distance (for visibility - 15 feet) would require hose weight of approximately 10 pounds. The minimum safe distance of 40 feet would require a hose weight of 15 pounds.

An analysis of wheeled systems based on Surveyor-obtained data on lunar soil properties (Reference 8) and basic equations of wheel mechanics (Reference 9) revealed the relationship shown in Figure 42 and labeled "without hoses."

As the wheel diameter (and weight) increases, the drawbar pull required decreases. The calculations were based on two wheels and a (180 + 300 =) 480 pounds LFV, which under reduced lunar gravity, would weigh 80 earth pounds so that each wheel would carry a load of 40 pounds. A two-inch wide tread was assumed. Surveyor data indicated such a wheel would sink approximately 1.2 inches into the lunar soil. A wheel with a 1-inch tread would sink significantly deeper and would tend to bury itself. A wider tread would increase the wheel weight almost proportionately.

Use of skids was considered and rejected because further analysis indicated that even with 10-inch wheels the drawbar pull required of a space-suited astronaut could exceed his capability (40 percentile astronaut weight, leaning at a 30-degree angle). Skids normally would require even more drawbar pull. The "without hoses" curve, however, needed to be adjusted to show the weight of the 25 feet of hoses that still would be required. When this adjustment was made, it was seen that a wheeled system could be used to move the LFV's in from beyond the 40-foot distance for a total weight of approximately 27 pounds (the weight of the wheel system with 25 feet of hoses for the estimated maximum pull capability), or for (27 - 15 =) 12 pounds more than the all-hoses system with hoses weighing 0.2 pounds per foot. Consequently, the use of hoses, without wheeled transport of the LFV's, appears to be the dominant solution to the refueling problem. The timelines incorporated this refueling mode.

REMOTE-SITE LAUNCH PADS

The soil-erosion analysis indicated that by cutting the engines at a nozzle height of 4 to 5 feet and dropping down, erosion ejecta would not present a problem. However, it is believed that the ejecta could be hazardous to the LFV and to the astronaut upon launch. A brief analysis to determine efficient means for reducing or eliminating this hazard found two possible solutions: the use of soil-stabilizing and adhering sprays, and the deployment of a ground cloth under the LFV. Recent and present studies at the Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio (T.O. 91008 and 91009) on Soil Stabilization and Rapid Site Construction were reviewed. These studies seek a lightweight, easily and quickly applied protective covering of electrolytes, resins, phosphates, and/or cements. In earth environment, these materials have proven rather promising. Ling-Temco-Vought Company manufactured and made available a plastic material that was sprayed onto a grass surface until a coating a few millimeters thick was built up. The Dornier DO 31, a jet VTOL transport aircraft, was able to land and take off from the prepared surface with ease. This same plastic is used to coat sand and gravel surfaces when they have to be used for helicopter operations. Drying time for the sprayed plastic in earth environment is about one hour for a 1/4-inch mat, capable of withstanding forward base V/STOL and helicopter operations under combat conditions. It is possible that a coating of a few mils would suffice for lunar launch of the LFV. However, the uncertainties of the lunar environment characteristics (i. e., vacuum, extreme surface temperatures) and lunar soil characteristics, coupled with the requirement that the LFV would need to be either moved or tilted to permit access to the soil, made the spray approach less attractive than the use of a ground cloth.

Several materials for ground cloths were investigated (Kaplon, carbon fibers, etc.). The most desirable substance appeared to be Kynol, made by the Carborundum Company. This material reportedly will resist an oxyacetylene flame (4500 F) for several minutes before becoming primarily a carbon char. A sample of this fiber was obtained. A visual and tactile inspection revealed no limitations that might preclude its use as a rocket plume deflector for launch/landing operations at the ELM or for launch at remote sites. The cloth could be deployed by staking or weighting down two corners, drawing the accordian-folded cloth under the vehicle (by means of a line passed under the legs of the LFV using the soil sampling tool), and then staking or weighting down the other two corners. A 5-by-5-foot cloth, adequate to protect the LFV during remote-site launches, would weigh approximately 2 pounds.

FUNCTIONAL ANALYSIS

A preliminary functional analysis during the study identified activities on both earth and moon that are essential for qualification and use of the LFV. These activities are identified in basic flow diagrams which, in the absence of an overall basic flow from NASA or firm test plan/requirements, are based upon the test philosophy established for Apollo and defined in MCP 500-10, "Apollo Test Requirements." The flow assumes complete acceptance test and checkout at Downey and prelaunch operations at KSC. Figures 43 through 52, in Appendix C, constitute the basic flow. Requirement allocation sheets itemizing a first- or lower-level flow activities were constructed for each of the nine functional areas identified grossly in Figure 43 and in detail in Figures 44 through 52. These itemizations can be extended during subsequent development phases to the depth necessary to establish total support requirements for LFV operations on both earth and moon.

PRELIMINARY SPECIFICATIONS

By analysis of the LFV designs, the functional flow diagrams, the requirements sheets and the planned lunar sortie operations, the listings of GSE and LSE end items in Tables 7 and 8 were developed. These lists will require review and updating during Phase C to maintain consonance with the vehicle as detail design requirements are finalized.

During Phase C and Phase D activities, an individual contractor end item (CEI) specification will be prepared to document each new or modified GSE and LSE end item. These end items will be designed in accordance with the requirements of specification number SS621M0002, "Performance and Design Requirements of the Ground System for the Command and Service Module/Apollo Applications Program, General Specifications for," dated 2-28-68.

1

Table 7. Ground Support Equipment

Model Number	Title	Remarks
AXX-001	LFV Protective Cover	Protects LFV from dust, etc., during inactive periods.
AXX-002	Electronic Weigh Set	Accurately measures LFV weights to locate c.g. and verify total vehicle weight (similar to Apollo H14-040 except total capacity will be approximately 1000 pounds).
A14-C28	Optical Alignment Set	Determines precise vertical plane for weight, balance, and engine nozzle alignment operations.
AXX-003	Weight Simulator Set	Calibrated weights: simulate propellant, astronaut and cargo loads during weight and balance operations.
AXX-004	Helium Tank Container	Stores and protects helium tanks before installation in vehicle.
AXX-005	Substitute Battery	Replaces LFV battery during tests.
AXX-006	Nozzle Cover Set	Protect engine nozzles during inactive periods.
AXX-007	Fluid Disposal and Leak-Test Nozzle Adapter Set	Enables leak-testing of engines and draining of propellants following engine operations (similar to Apollo A14-146 and A14-179).
AXX-008	Battery Charger	Recharges LFV battery as required to support tests.
CXX-001	Transducer Substitute Unit	Enables activation of control and monitor panel displays during checkouts.
*C14-075	Propulsion Systems Checkout Unit	Provides regulated GN_2 sources and metering devices for functional testing of propulsion system components and leak-testing of total system.
*C14-630	Universal FDS Control Unit	Controls valves on fluid distribution systems during checkout and servicing.

Table 7. Ground Support Equipment (Cont)

Model Number	Title	Remarks
CXX-022	Gas Flow Tester	Verifies gas flow through engine nozzles during system testing (similar to Apollo C14-471, plus an indicator panel).
CXX-003	Gyro Test Console	Provides power, controls, and display devices to verify rate gyro operations.
CXX-004	Electrical Cable Set	Connects LFV, facility power sources and electrical GSE end items.
HXX-001	Support Stand	Supports LFV during tests.
HXX-002	LFV Sling	Enables hoisting of vehicle.
HXX-003	Weight and Balance Set	Used with electronic weigh set to measure total vehicle weight and determine vehicle c.g.
HXX-004	Rotation Fixture	Rotates and positions vehicle 90 degrees during balance and c.g. operations.
SXX-001	Hose Set	Connects LFV to facility and fluid distribution systems.
*S14-002	Oxidizer Transfer Conditioning Unit	Service oxidizer system.
*S14-057	RCS Oxidizer Servicing Unit	
*S14-059	Oxidizer Ready Storage Unit	
*S14-061	Oxidizer Toxic Vapor Disposal Unit	
*S14-008	Fuel Transfer/Conditioning Unit	Service fuel system.
*S14-063	S/M RCS, Fuel Servicing Unit	

Table 7. Ground Support Equipment (Cont)

Model Number	Title	Remarks
*S14-058	Fuel Ready Storage Unit	Service fuel system.
*S14-060	Fuel Toxic Vapor Disposal Unit	
*S14-014	Fluid Distribution Systems	Connect/control fluids and gases between LFV and various facilities or servicing units (model number used depends on test location).
*S14-041		
*S14-082		
*S14-088		
*S14-128		
*S14-130		
*and/or S14-132		
*S14-009	Helium Transfer Unit	Service helium tanks
*S14-022	Helium Booster Unit	
*S14-062	Helium Ready Storage Unit	

*Existing Apollo/LEM equipment usable for support of LFV operations (may require some modifications).

Table 8. Lunar Support Equipment

Model Number	Title	Remarks
AXX-101	Weigh Kit	Spring scale and set of nomographs: determine weight and c.g. location before flight.
AXX-102	LM Base Landing Pad	Flexible ground cover with tie-down devices: used at LM site to prevent soil erosion and particle dispersal during takeoff and landing.
AXX-103	Remote Site Takeoff Pad	Similar to AXX-102, except smaller and lighter for remote-site takeoff.
AXX-104	Towing Harness	Flexible line with shoulder strap and LFV attach fitting: used to drag LFV from LEM to landing pad, and to help position LFV for takeoff.
AXX-105	Deployment Device	Used to remove LFV from storage position on LM and lower it to lunar surface.
AXX-106	Helium Tank Carrier	Rack provides protection and pickup capability to facilitate transport of helium tanks from LM to LFV.
AXX-107	Landing Pylons	Bright-colored strips of material to be placed on lunar surface of LM base to help astronaut position LFV over landing pad.
CXX-101	Transducer Substitute Unit	Decapot simulates transducer output for checkout of panel display meters.
SXX-101	Fuel Servicing Set	Fuel hose and fuel vent adapter (hose, sight glass and pressure relief value): used to refuel LFV from LM tanks.
SXX-102	Oxidizer Servicing Set	Same as SXX-101, except for oxidizer system.

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APPENDIX A

DERIVATION OF SIMPLIFIED TRAJECTORY MODELS

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DERIVATION OF SIMPLIFIED TRAJECTORY MODELS

This section documents the modified ballistic and constant-altitude-trajectory equations developed for the lunar flying vehicle. Several simplifying assumptions were made:

a. Flat moon

b. No lunar atmosphere

c. Constant lunar gravity

d. Constant T/W

MODIFIED BALLISTIC TRAJECTORY

Two cases are presented. In the first, the thrust is reduced to zero after the boost (coast phase) until the deboost phase. In the second, there is a small thrust during the coast phase. The throttling ratio and thrust vector attitude can be changed to yield a variety of trajectory profiles.

List of Terms

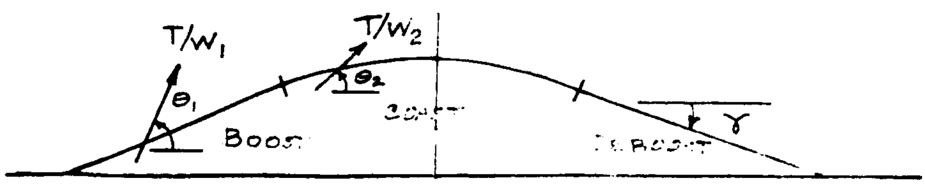
T/W_1 - boost thrust-to-weight ratio

T/W_2 - coast thrust-to-weight ratio

θ_1 - boost thrust attitude with respect to the horizontal

θ_2 - coast thrust attitude with respect to the horizontal

γ - flight path angle with respect to the horizontal



First consider a simplified case where the thrust during the coast phase is zero (e.g., a free falling projectile). The boost range is

$$R_{BOOST} = V_{x_1}{}^2 / 2 A_{x_1} \tag{1}$$

From Figures 1 (a) and (b)

$$V_{x_1} = \Delta V_1 \cos \theta_1 \tag{2}$$

$$A_{x_1} = g \; T/W_1 \cos \theta_1 \tag{3}$$

Therefore

$$R_{BOOST} = \frac{\Delta V_1{}^2}{2 \, g \; T/W_1} \cos \theta_1 \tag{4}$$

Since there is no thrust during the coast phase, the range from burnout to the midpoint is simply

$$R_{COAST_{MP}} = V_{x_1} \; t_2 \tag{5}$$

where

$$t_2 = V_{y_1}/g \qquad (V_{y_1} > 0)$$

Therefore

$$R_{COAST_{MP}} = \frac{V_{x_1} \; V_{y_1}}{g} \tag{6}$$

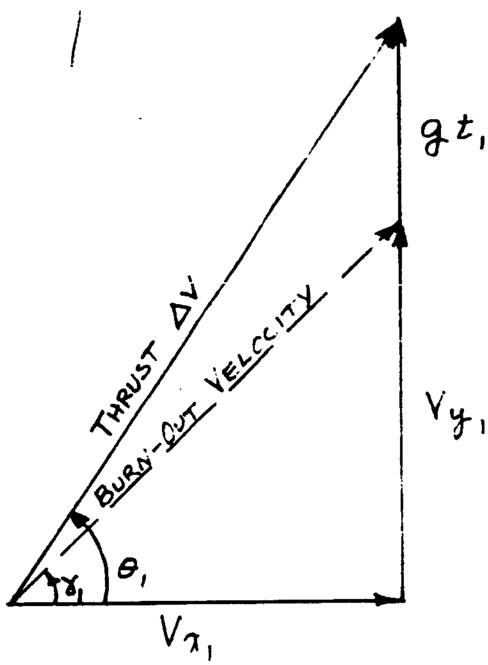
Referring to Figure 1a

$$V_{x_1} = \Delta V_1 \cos \theta_1 \tag{7}$$

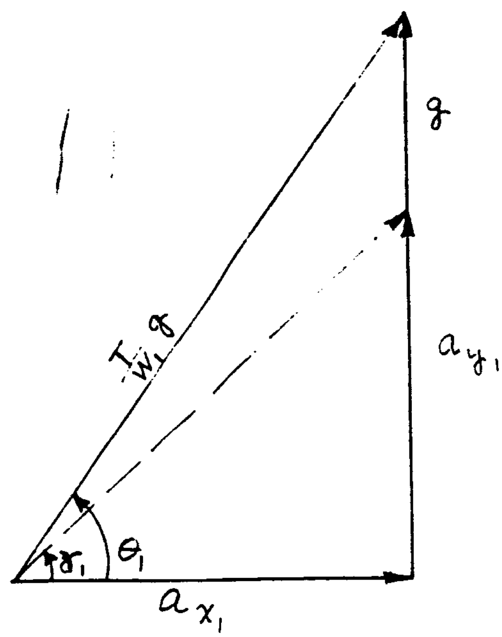
$$V_{y_1} = \Delta V_1 \sin \theta_1 - g \, t_1 \tag{8}$$

where

$$t_1 = \frac{V_{x_1}}{A_{x_1}} = \frac{V_{x_1}}{g \; T/W_1 \cos \theta_1}$$



a. Boost Velocity Polygon



b. Boost Instantaneous Acceleration Polygon

Figure 1.

so that

$$V_{y_1} = \Delta V_1 \left(\sin \theta - \frac{1}{T/W_1}\right) \tag{9}$$

Hence

$$R_{COAST_{MP}} = \frac{\Delta V_1{}^2}{g} \cos \theta_1 \left(\sin \theta_1 - \frac{1}{T/W_1}\right) \tag{10}$$

From Eq (4) and (10) the range from launch to the midpoint is

$$R_{MP} = R_{BOOST} + R_{COAST_{MP}} \tag{11}$$

or

$$R_{MP} = \frac{\Delta V_1{}^2 \cos \theta_1}{T/W_1 \; g} \left(T/W_1 \sin \theta_1 - 1/2\right) \tag{12}$$

where there is no thrust during the coast phase.

For determination of the optimum boost thrust attitude, θ_1, the partial of Equation (12) with respect to θ_1 is equated to zero:

$$\frac{\partial R}{\partial \theta} = 0 = \frac{\Delta V_1{}^2}{T/W_1 \; g} \left[- \sin \theta_1 \left(T/W_1 \sin \theta_1 - 1/2\right) + \left(T/W_1 \cos^2 \theta_1\right)\right] \tag{13}$$

or

$$- T/W_1 \sin^2 \theta_1 + 1/2 \sin \theta_1 + T/W_1 \left(1 - \sin^2 \theta_1\right) = 0 \tag{14}$$

Simplifying yields

$$- 2 \; T/W_1 \sin^2 \theta_1 + 1/2 \sin \theta_1 + T/W_1 = 0 \tag{15}$$

From the quadratic formula

$$\sin \theta_{1opt} = \frac{1 + \sqrt{1 + 32 (T/W_1)^2}}{8 \; T/W_1} \tag{16}$$

With θ_1 optimized, the optimum flight path angle can be determined by referring to Figure 1 (b).

$$g\ T/W_1 \sin\theta_1 = g + A \sin\gamma_1 \tag{17}$$

$$g\ T/W_1 \cos\theta_1 = A \cos\gamma_1 \tag{18}$$

or

$$T/W_1 (\sin\theta_1 - \cos\theta_1 \tan\gamma_1) = 1 \tag{19}$$

therefore

$$\tan\gamma_{1_{opt}} = \frac{\sin\theta_{1_{opt}} - \left(\frac{1}{T/W_1}\right)}{\cos\theta_{1_{opt}}} \tag{20}$$

Now, adding thrust during the coasting phase, the midpoint coast range becomes

$$R_{COAST_{MP}} = V_{x_1} t_2 + (1/2) A_{x_2} t_2^2 \tag{21}$$

where

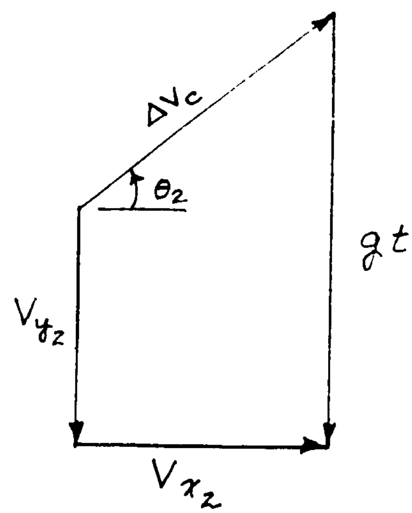
$$t_2 = \frac{V_{y_1}}{-A_{y_2}} \tag{22}$$

Referring to Figures 2a and 2b

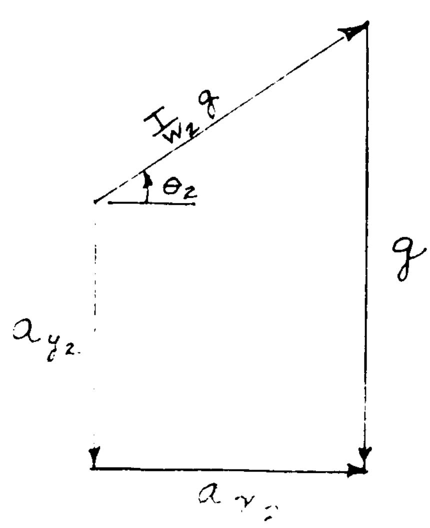
$$A_{y_2} = T/W_2\ g \sin\theta_2 - g \tag{23}$$

$$A_{x_2} = T/W_2\ g \cos\theta_2 \tag{24}$$

Substituting Equations (22), (23), and (24) into (21) yields



a. Coast Velocity Polygon



b. Coast Instantaneous Acceleration Polygon

Figure 2.

$$R_{COAST_{MP}} = -\frac{\Delta V_1^{\,2} \cos\theta_1 \left(\sin\theta_1 - \frac{1}{T/W_1}\right)}{T/W_2\, g \left(\sin\theta_2 - \frac{1}{T/W_1}\right)} + \frac{\Delta V_1^{\,2} \cos\theta_2 \left(\sin\theta_1 - \frac{1}{T/W_1}\right)^2}{2\, T/W_2\, g \left(\sin\theta_2 - \frac{1}{T/W_2}\right)^2} \tag{25}$$

Therefore, the range from launch to the midpoint, using a small thrust during the coast phase, is

$$R_{MP} = R_{BOOST} + R_{COAST_{MP}}$$

or

$$R_{MP} = \frac{\Delta V_1^{\,2} \cos\theta_1}{2\, T/W_1\, g} - \frac{\Delta V_1^{\,2} \cos\theta_1 \left(\sin\theta_1 - \frac{1}{T/W_1}\right)}{T/W_2\, g \left(\sin\theta_2 - \frac{1}{T/W_2}\right)} + \frac{\Delta V_1^{\,2} \cos\theta_2 \left(\sin\theta_1 - \frac{1}{T/W_1}\right)^2}{2\, T/W_2\, g \left(\sin\theta_2 - \frac{1}{T/W_2}\right)^2} \tag{26}$$

The total impulse is

$$\Delta V_T = 2\left[\Delta V_1 + \Delta V_{2_{MP}}\right] \tag{27}$$

where

$$\Delta V_{2_{MP}} = \frac{T}{W_2}\, g\, t_2 \tag{28}$$

or

$$\Delta V_{2_{MP}} = \frac{T}{W_2}\, g\, \frac{V_{y_1}}{-A_{y_2}} \tag{29}$$

From Figure 2b

$$A_{y_2} = \frac{T}{W_2} g \left(\sin \theta_2 - \frac{1}{T/W_2}\right) \tag{30}$$

Substituting Eq (9) and (30) into (29) yields

$$\Delta V_{2_{MP}} = - \Delta V_1 \frac{\left(\sin \theta_1 - \frac{1}{T/W_1}\right)}{\left(\sin \theta_2 - \frac{1}{T/W_1}\right)} \tag{31}$$

so that

$$\Delta V_T = 2 \ \Delta V_1 \left(1 - \frac{\sin \theta_1 - \frac{1}{T/W_1}}{\sin \theta_2 - \frac{1}{T/W_2}}\right) \tag{32}$$

or

$$\Delta V_1 = \left(\frac{D_2}{D_2 - D_1}\right) \frac{\Delta V_T}{2} \tag{33}$$

where

$$D_1 = \sin \theta_1 - \frac{1}{T/W_1} \tag{34}$$

$$D_2 = \sin \theta_2 - \frac{1}{T/W_2} \tag{35}$$

The optimum boost and coast thrust attitudes occur at the maximum of the following expression:

$$F = \frac{R_T}{\Delta V_T^{\ 2}} \tag{36}$$

or from Eq (32) and (26)

$$F = \frac{1}{2\,g}\left(\frac{D_2}{D_2 - D_1}\right)^2 \left[\frac{\cos\theta_1}{2\,T/W_1} - \frac{\cos\theta_1\,D_1}{T/W_2\,D_2} + \frac{\cos\theta_2\,D_1^{\,2}}{2\,T/W_2\,D_2^{\,2}}\right] \tag{37}$$

Rather than differentiating Eq (37) to obtain the optimum θ_1 and θ_2, the solution was obtained graphically by assuming $\theta_{1_{opt}} \approx \theta_{2_{opt}}$, which has a negligible effect on the ΔV requirement.

The maximum altitude is

$$Z_{MAX} = \frac{V_{y_1}^{\,2}}{2\,A_{y_1}} - \frac{V_{y_1}^{\,2}}{2\,A_{y_2}} = \frac{V_{y_1}^{\,2}}{2}\left(\frac{1}{A_{y_1}} - \frac{1}{A_{y_2}}\right) \tag{38}$$

From Eq (9) and (33)

$$V_{y_1} = \frac{\Delta V_T\,D_1\,D_2}{2\,(D_2 - D_1)} \tag{39}$$

From Figure 1b

$$A_{y_1} = T/W_1\,g\left(\sin\theta_1 - \frac{1}{T/W_1}\right) \tag{40}$$

or

$$A_{y_1} = T/W_1\,g\,D_1 \tag{41}$$

From Eq (30) and (35)

$$A_{y_2} = T/W_2\,g\,D_2 \tag{42}$$

Therefore

$$Z_{MAX} = \frac{\Delta V_T^{\,2}\, D_1^{\,2}\, D_2^{\,2}}{8\,(D_2 - D_1)^2} \left(\frac{1}{T/W_1\, g\, D_1} - \frac{1}{T/W_2\, g\, D_2} \right) \tag{43}$$

or

$$Z_{MAX} - \frac{\Delta V_T^{\,2}\, D_1\, D_2}{8\, g\,(D_2 - D_1)^2} \left(\frac{D_2}{T/W_1} - \frac{D_1}{T/W_2} \right) \tag{44}$$

The following summarizes the key equations:

Midpoint range with zero thrust during coast phase:

$$R_{MP} = \frac{\Delta V_1^{\,2} \cos \theta_1}{T/W_1\, g} (T/W_1 \sin \theta - 1/2) \tag{12}$$

Optimum boost thrust attitude with no coast thrust:

$$\sin \theta_{1_{opt}} = \frac{1 + \sqrt{1 + 32\,(T/W_1)}^{\,2}}{8\; T/W_1} \tag{16}$$

Optimum flight path angle using (16) for $\theta_{1_{opt}}$:

$$\tan \gamma_{1_{opt}} = \frac{\sin \theta_{1_{opt}} - \frac{1}{T/W_1}}{\cos \theta_{1_{opt}}} \tag{20}$$

Midpoint range with thrust during coast phase:

$$R_{MP} = \frac{\Delta V_1^{\,2} \cos\theta_1}{2\,T/W_1\, g} - \frac{\Delta V_1^{\,2} \cos\theta_1 \left(\sin\theta_1 - \frac{1}{T/W_1}\right)}{T/W_2\, g \left(\sin\theta_2 - \frac{1}{T/W_2}\right)}$$

$$+ \frac{\Delta V_1^{\,2} \cos\theta_2 \left(\sin\theta_1 - \frac{1}{T/W_1}\right)^2}{2\,T/W_2\, g \left(\sin\theta_2 - \frac{1}{T/W_2}\right)^2} \tag{26}$$

By assuming $\theta 1_{opt} \approx \theta 2_{opt}$, one can obtain graphically the optimum thrust vector attitude for thrust during the coast by determining the value of θ_1 or θ_2 that maximizes the following expression:

$$F = \frac{R_T}{\Delta V_T^{\,2}} = \frac{1}{2\,g}\left(\frac{D_2}{D_2 - D_1}\right)^2 \left(\frac{\cos\theta_1}{2\,T/W_1} - \frac{\cos\theta_1}{T/W_2}\frac{D_1}{D_2} + \frac{\cos\theta_2}{2\,T/W_2}\frac{D_1^{\,2}}{D_2^{\,2}}\right) \tag{37}$$

where

$$D_1 = \sin\theta_1 - \frac{1}{T/W_1}$$

$$D_2 = \sin\theta_2 - \frac{1}{T/W_2} \tag{34}$$

Maximum altitude with thrust during coast phase:

$$Z_{MAX} = \frac{\Delta V_T^{\,2}\, D_1\, D_2}{8\, g\, (D_2 - D_1)^2}\left(\frac{D_2}{T/W_1} - \frac{D_1}{T/W_2}\right) \tag{44}$$

CONSTANT ALTITUDE TRAJECTORY

The following assumptions were made in deriving the relationships for the constant altitude case:

a. Flat moon

b. Constant lunar gravity

c. Constant T/W and vehicle attitude angle for each trajectory segment

For the horizontal and vertical accelerations, the relationships are

$$\frac{1}{g}\frac{dV}{d_t} = T/W \cos\theta \tag{45}$$

$$T/W \sin\theta = 1 \tag{46}$$

Integrating Eq (45) from the time of flight initiation at attitude angle θ from the horizontal to the cruise velocity condition (t_c = cruise time and t_t = time to mid-range):

$$\frac{Vc}{gt_t} = (T/W) \cos\theta \frac{t_c}{tt} \tag{47}$$

$$\frac{R}{2\, gt_t^{\,2}\,(T/W) \cos\theta} = 1/2 \left(\frac{t_c}{t_t}\right)^2 + \frac{t_c}{t_t}\left(1 - \frac{t_c}{t_t}\right) \tag{48}$$

$$\frac{\Delta V}{2\, gt_t} = \frac{t_c}{t_t}(T/W - 1) + 1 \tag{49}$$

Combining Eq (47), (48), and (49)

$$\frac{\Delta V}{2\, g} = \frac{(T/W - 1/2)\, V_c}{g\, T/W \cos\theta} + \frac{R}{2\, V_c} \tag{50}$$

Differentiating Eq (50),

$$\frac{\partial \Delta V}{\partial V_c} = 2\, g \left[\frac{(2\, T/W - 1)}{2\, g\, T/W \cos\theta} - \frac{R}{2\, V_c^{\,2}}\right] \tag{51}$$

From which the cruise velocity for minimum ΔV is given by

$$V_{c_{\Delta V_{MIN}}} = \sqrt{\frac{R\ g\ (T/W)\cos\theta}{2\ (T/W) - 1}} \tag{52}$$

Substituting Eq (52) into (50),

$$\frac{\Delta V_{MIN}}{\sqrt{R}} = 2\sqrt{\frac{(2\ T/W - 1)\ g}{T/W\ \cos\theta}} \tag{53}$$

$$= 2\sqrt{\frac{g\ (2 - \sin\theta)}{\cos\theta}} \tag{54}$$

since

$$T/W \sin\theta = 1 \tag{55}$$

By differentiating Eq (54) with respect to θ, the value of θ for which $\Delta V_{MIN}/\sqrt{R}$ is minimum is found to be $\theta = 30$ degrees (60 degrees from the vertical).

APPENDIX B

MISSION TIMELINES

Table 9. Nominal Three-Day Dawn Mission Time Line With Two LFV's

Assumptions/Constraints:

- Lunar dawn landing with 10-degree sun angle at landing (-50°) and 47-degree sun angle at liftoff (180 F)
- Lunar equatorial region mission (±15° lat)
- Three-day lunar surface staytime
- Two-man ELM with 2 LFV's and an advanced ALSEP
- Eleven hours of personal maintenance/rest per day
- 1000 pounds of propellant

Event Start Time	Lunar Stay Time Events		Event Duration Time
:00	ELM touchdown on lunar surface, surface temp -50 F		-
:00	Checkout and activation of ELM for lunar stay		2:00
	Postlanding checkout	:30	
	Launch simulation	1:30	
2:00	Science conference with earth		:30
2:30	Personal maintenance (lunch and rest)		1:00
3:30	Preparation for EVA		:30
	Don and check out PLSS	:25	
	Dump cabin pressure and egress	:05	
4:00	EVA (1 and 2), surface temp -20 F		3:00
	ELM inspection	:20	
	Erection of solar array	:20	
	Erection of radiator	:30	
	Erection of antenna	:20	
	Dismount LFV's (2)	:20	
	Assemble LFV's (2), mount scientific equip. on LFV 1	:10	
	Set up landing mats and aids 40 feet from ELM	:20	
	Move LFV 1 to mat 1	:05	
	Check out LFV 1 (electronics/controls)	:10	
	Move LFV 2 to mat 2	:05	
	Check out LFV 2 (electronics/controls)	:10	
	Deploy fuel and oxidizer hoses and battery recharge cables	:10	
7:00	Ingress to ELM and hook up ELM ECS		:10
7:10	Repressurize ELM and doff pressure suits		:20
7:30	Personal maintenance (supper)		1:00
8:30	Housekeeping and maintenance check		1:00
9:30	Sleep		7:00
16:30	Personal maintenance (breakfast)		1:00
17:30	Preparation for EVA		1:00
	Don and check out pressure suits	:30	
	Don and check out PLSS	:25	
	Dump cabin pressure and egress	:05	
18:30	EVA (3 and 4), surface temp 45 F		3:00
	Start setting up advanced ALSEP	:50	
	Fuel LFV 1 on mat and mount helium tank	:25	
	Fuel LFV 2 on mat and mount helium tank	:25	

Table 9. Nominal Three-Day Dawn Mission Time Line With Two LFV's (Cont)

Event Start Time	Lunar Stay Time Events			Event Duration Time
	Scientist astronaut 1 LFV qualification flight		:50	
	Check out LFV	:10		
	Flight out - 0.5 nmi	:03		
	Postlanding check out	:05		
	Deploy launching mat	:10		
	Local exploration	:10		
	Preflight checkout	:05		
	Flight back - 0.5 nmi	:02		
	Postlanding checkout	:05		
	Scientist astronaut 2			
	Monitors flight	:20		
	Completes setting up ALSEP	:30		
	Move science equipment from LFV 1 to LFV 2		:10	
	Scientist astronaut 2 LFV qualification flight (Same as scientist astronaut 1)		:50	
	Scientist astronaut 1			
	Monitors flight	:20		
	Refuels LFV 1 - deploys thermal blanket and connects battery and recharge cable	:30		
	Refuels LFV 2 - deploys thermal blanket and connect battery and recharge cable (S/A 1 & 2)		:20	
21:30	Ingress to ELM and hook up ELM ECS			:10
21:40	Repressurize ELM and doff pressure suits			:20
22:00	Personal maintenance (lunch and rest)			1:00
23:00	Science conference with earth			1:00
24:00	Preparation for EVA (same as hour 17:30)			1:00
25:00	EVA (5) scientist astronaut 2 surface temp 85 F			3:00
	Uncover LFV and replace helium tanks		:10	
	Scientist astronaut 1 monitors	2:10		
	Scientist astronaut 2:		2:10	
	Check out LFV 2	:10		
	Flight out - 7 nmi	:04		
	Postlanding checkout	:05		
	Deploy launching mat	:10		
	Local exploration	1:27		
	Preflight checkout	:05		
	Flight back - 7 nmi	:04		
	Postlanding checkout	:05		
	Refuel LFV 2 - deploy thermal blankets: replace helium tank and battery and recharge cable		:30	
	Move scientific equip. from LFV 2 to LFV 1		:10	
28:00	Ingress to ELM and hook up ELM ECS			:10
28:10	Repressurize ELM and doff pressure suits			:20
28:30	Personal maintenance (supper)			1:00
29:30	Review results of sorties with earth scientists			1:00

Table 9. Nominal Three-Day Dawn Mission Time Line With Two LFV's (Cont)

Event Start Time	Lunar Stay Time Events		Event Duration Time
30:30	Housekeeping and maintenance check		1:00
31:30	Sleep		8:00
39:30	Personal maintenance (breakfast)		1:00
40:30	Preparation for EVA (same as hour 17:30)		1:00
41:30	EVA (6), scientist astronaut 1, surface temp 130 F		3:00
	Scientist astronaut 1:		
	Checks out LFV 1	:10	
	Multiple stop flight	2:40	
	Moves scientific equip. to LFV 2	:10	
	Scientist astronaut 2 monitors		
44:30	Ingress to ELM and hook up ELM-ECS		:10
44:40	Repressurize ELM and doff pressure suits		:20
45:00	Personal maintenance (lunch and rest)		1:00
46:00	Science conference with earth		1:00
47:00	Preparation for EVA (same as hour 17:30)		1:00
48:00	EVA (7) scientist astronaut 2 - surface temp 150 F		3:00
	Scientist astronaut 1 monitors		
	Scientist astronaut 2		
	Checks out LFV 2	:10	
	Multiple stop flight within walk-back range	2:50	
51:00	Ingress to ELM and hook up ELM-ECS		:10
51:10	Repressurize ELM and doff pressure suits		:20
51:30	Personal maintenance (supper)		1:00
52:30	Housekeeping and maintenance check		1:00
53:30	Sleep		8:00
61:30	Personal maintenance (breakfast)		1:00
62:30	Preparation for final EVA's (same as hour 17:30)		1:00
63:30	EVA (8 and 9), surface temp 165 F		3:00
	Sample selection		
	Sample storage		
	Check ALSEP		
	Check out ELM ascent stage		
66:30	Ingress to ELM and hook up ELM ECS		:10
66:40	Repressurize ELM		:05
66:45	Personal maintenance (lunch and rest)		1:00
67:45	Prelaunch countdown and checkout		3:00
70:45	Liftoff - surface temp 175 F		-

Table 10. Three-Day Lunar Sunset Mission Time Lines With Two LFV's

Assumptions/Constraints:

- Lunar pre-sunset landing with 20-degree sun angle at landing, (80 F) and terminator 17 degrees away - past sunset - at liftoff (-220 F)
- Three-day lunar surface stay time
- Two-man ELM with 2 LFV and an advanced ALSEP
- Eleven hours of personal maintenance/rest per man per day
- 1000 lbs of residual propellants available

Event Start Time	Lunar Stay Time Events			Event Duration Time
:00	ELM touchdown on lunar surface - surface temp 80 F			-
:00	Checkout and activation of ELM for lunar stay			2:00
	Postlanding checkout		:30	
	Launch simulation		1:30	
2:00	Science conference with earth			:30
2:30	Personal maintenance (lunch and rest)			1:00
3:30	Preparation for EVA			:30
	Don and checkout PLSS		:25	
	Dump cabin pressure and egress		:05	
3:00	EVA (1 & 2), surface temp 65 F			3:00
	ELM inspection		:20	
	Erection of solar array		:20	
	Erection of radiator		:30	
	Erection of antenna		:20	
	Dismount LFV's (2)		:20	
	Assemble LFV's (2) - mount scientific equip on LFV 1		:10	
	Set up landing mats and aids 40 feet from ELM		:20	
	Move LFV 1 to mat 1		:05	
	Checkout LFV 1 (electronics/controls)		:10	
	Move LFV 2 to mat 2		:05	
	Checkout LFV 2 (electronics/controls)		:10	
	Deploy fuel and oxidizer hoses and battery recharge		:10	
7:00	Ingress to ELM and hook up ELM ECS			:10
7:10	Repressurize ELM and doff pressure suits			:20
7:30	Personal maintenance (supper)			1:00
8:30	Housekeeping and maintenance check			1:00
9:30	Sleep			7:00
16:30	Personal maintenance (breakfast)			1:00
17:30	Preparation for EVA			1:00
	Don and checkout pressure suits		:30	
	Don and checkout PLSS		:25	
	Dump cabin pressure and egress		:05	
18:30	EVA (3 & 4), surface temp 0 F			3:00
	Start setting up advanced ALSEP	:50	:50	
	Fuel LFV 1 on mat; mount helium tank	:25		
	Fuel LFV 2 on mat; mount helium tank	:25		

Table 10. Three-Day Lunar Sunset Mission Time Lines With Two LFV's (Cont)

Event Start Time	Lunar Stay Time Events			Event Duration Time
	Scientist astronaut 1 LFV qual flt		:50	
	Checkout LFV	:10		
	Flight out - 0.5 nmi	:03		
	Postlanding checkout	:05		
	Deploy launching mat	:10		
	Local exploration	:10		
	Preflight checkout	:05		
	Flight back - 0.5 nmi	:02		
	Postlanding checkout	:05		
	Scientist astronaut 2			
	Monitors flight	:20		
	Completes setting up ALSEP	:30		
	Move scientific equip. from LFV 1 to LFV 2		:10	
	Scientist astronaut 2 LFV qual flt (Same as scientist astronaut 1)		:50	
	Scientist astronaut 1			
	Monitors flight	:20		
	Refuels LFV 1 - deploys thermal blanket and connects battery and recharge cable	:30		
	Refuels LFV 2 - deploys thermal blanket and connects battery and recharge cable (S/A 1 & 2)		:20	
21:30	Ingress to ELM and hook up ELM ECS			:10
21:40	Repressurize ELM and doff pressure suits			:20
22:00	Personal maintenance (lunch & rest)			1:00
23:00	Preparation for EVA (same as hour 17:30)			1:00
24:00	EVA (5), scientist astronaut 2, surface temp -20 F			3:00
	Uncover LFV and replace helium tanks		:10	
	Scientist astronaut 1 monitors		2:10	
	Scientist astronaut 2:		2:10	
	Checkout LFV 2	:10		
	Flight out - 7 nmi	:04		
	Postlanding checkout	:05		
	Deploys launching mat	:10		
	Local exploration	1:27		
	Preflight checkout	:05		
	Flight back - 7 nmi	:04		
	Postlanding checkout	:05		
	Refuel LFV 2 - deploy thermal blankets: service helium tank and batteries		:30	
	Move scientific equip. from LFV 2 to LFV 1		:10	
27:00	Ingress to ELM and hook up ELM ECS			:10
27:10	Repressurize ELM and doff pressure suits			:20
27:30	Personal maintenance (supper)			1:00
28:30	Housekeeping and maintenance check			1:00

Table 10. Three-Day Lunar Sunset Mission Time Lines With Two LFV's (Cont)

Event Start Time	Lunar Stay Time Events		Event Duration Time
29:30	Sleep		8:00
37:30	Personal maintenance (breakfast)		1:00
38:30	Preparation for EVA (same as hour 17:30)		1:00
30:30	SUNSET		
39:30	EVA (6), scientist astronaut 1, surface temp -100 F		3:00
	Scientist astronaut 1:		
	Records and investigates sunset phenomena	1:00	
	Checks out LFV 1	:10	
	Multiple-stop flight (earthshine)	1:40	
	Moves scientific equip. to LFV 2	:10	
	Scientist astronaut monitors		
42:30	Ingress to ELM and hook up ELM ECS		:10
42:40	Repressurize ELM and doff pressure suits		:20
43:00	Personal maintenance (lunch and rest)		1:00
44:00	Review scientific findings with earth scientists		2:00
46:00	Preparation for EVA (same as hour 17:30)		1:00
47:00	EVA (7), scientist astronaut 2, surface temp -170 F		3:00
	Scientist astronaut 1 monitors		
	Scientist astronaut 2		
	Checks out LFV 2	:10	
	Multiple stop flight withing walk-back range (earthshine)	2:50	
50:00	Ingress to ELM and hook up ELM ECS		:10
50:10	Repressurize ELM and doff pressure suits		:20
50:30	Personal maintenance (supper)		1:00
51:30	Review scientific findings with earth scientists		1:00
52:30	Housekeeping and maintenance check		1:00
53:30	Sleep		8:00
61:30	Personal maintenance (breakfast)		1:00
62:30	Preparation for final EVA's (same as hour 17:30)		1:00
63:30	EVA (8 & 9), surface temp -200 F		3:00
	Sample selection		
	Sample storage		
	Check ALSEP		
	Check out ELM ascent stage		
66:30	Ingress to ELM and hook up ELM ECS		:10
66:40	Repressurize ELM		:05
66:45	Personal maintenance (lunch and rest)		1:00
67:45	Prelaunch countdown and check out		3:00
70:45	Liftoff - surface temp -220 F		-

Table 11. 14-Day Daylight Mission Time Line With Two LFV's

Assumptions/Constraints:

- Lunar dawn landing (10-degree sun angle at landing, -50 F, 0-degree sun angle at liftoff, -100 F
- Lunar equatorial region mission (±15° lat)
- 14-day lunar surface stay time
- Lunar logistics cargo vehicle (LCV) landed 0.5 nmi from ELM
- LFV propellant payload: 1000 pounds usable residuals in ELM descent stage, 1000 pounds in logistics/cargo vehicle
- 2-man ELM with 2 LFV's; third scientist astronaut remains in CSM in lunar orbit
- 11 hours of personal maintenance/rest per man per day

Event Start Time	Event		Event Duration Time
:00	ELM touchdown on lunar surface 0.5 nmi from logistic cargo lander. Surface temp -50 F		-
:00	Checkout and activation of ELM for lunar stay		2:00
	Postlanding checkout	:30	
	Launch simulation	1:30	
2:00	Personal maintenance (lunch and rest)		1:00
3:00	Preparation for EVA		:30
	Don and checkout PLSS	:25	
	Dump cabin pressure and egress	:05	
3:30	EVA 1 and 2 Surface temp -30 F		3:00
	ELM inspection	:20	
	Erection of solar array	:20	
	Erection of radiator	:30	
	Erection of antenna	:20	
	Dismount LFV's (2)	:20	
	Assemble LFV's	:10	
	Set up landing mats and aids 40 feet from ELM	:20	
	Move LFV 1 to Mat 1	:05	
	Checkout LFV 1 (electronics and controls)	:10	
	Move LFV 2 to Mat 2	:05	
	Checkout LFV 2 (electronics and controls)	:10	
	Deploy fuel, oxidizer, and helium hoses and battery recharger cables	:10	
6:30	Ingress to ELM and hook up ELM ECS	:10	
6:40	Repressurize ELM and doff pressure suits	:20	
7:00	Personal maintenance (supper)	1:00	1:00
8:00	Housekeeping and maintenance check		1:00
9:00	Sleep		7:00
16:00	Personal maintenance (breakfast)		1:00

Table 11. 14-Day Daylight Mission Time Line With Two LFV's (Cont)

Event Start Time	Event			Event Duration Time
17:00	Preparation for EVA			1:00
	Don and checkout pressure suits		:30	
	Don and checkout PLS		:25	
	Dump cabin pressure and egress		:05	
18:00	EVA 3 and 4, surface temp 40 F			3:00
	Scientist astronaut 1:			
	Fuels LFV's 1 and 2 and pressurizes He tanks		:25	
	Checks out LFV 1		:10	
	Flies to LCV 0.5 nmi		:03	
	Conducts postlanding checkout		:05	
	Activates LCV systems		:20	
	Deploys LFV landing mats and aids 40 feet from LCV		:20	
			:05	
	Conducts preflight checkout		:05	
	Flies to ELM site, 0.5 nmi		:02	
	Conducts postlanding checkout		:05	
	Refuels LFV 1 and pressurizes He tanks; recharge batteries		:25	
	Completes deploying advanced ALSPE and monitors flight		:60	
	Scientist astronaut 2:			
	Fuels LFV's 1 and 2 and pressurizes He tanks		:25	
	Checks out LFV 2		:10	
	Begins deploying advanced ALSEP and monitors flight		1:25	
	Flies to LCV 0.5 nmi		:03	
	Conducts postlanding checkout		:05	
	Continues activation of LCV		:15	
	Conducts preflight checkout		:05	
	Flies to ELM site, 0.5 nmi		:02	
	Conducts postlanding checkout		:05	
	Refuels LFV 2 and pressurizes He tanks; recharge batteries		:25	
21:00	Ingress to ELM and hook up ELM ECS			:10
21:10	Repressurize ELM and doff pressure suits			:20
21:30	Personal maintenance (lunch and rest)			1:00
22:30	Status conference with Earth			1:00
23:30	Preparation for EVA (same as hour 17:00)			1:00
24:30	EVA 5 and 6, surface temp 80 F			3:00
	Make ELM dormant (thermal shroud?)		1:00	
	Checkout LFV 1 and 2		:10	
	Scientist astronaut 1:			
	Flies to LCV 0.5 nmi	:02	:27	
	Conducts postlanding checkout	:05		
	Dismounts scientific equipment and straps on LFV 1	:20		
	Scientist astronaut 2:			
	Checks advanced ALSEP array; monitors flt	:20	:27	
	Flies to LCV, 0.5 nmi	:02		
	Conducts postlanding checkout	:05		

Table 11. 14-Day Daylight Mission Time Line With Two LFV's (Cont)

Event Start Time	Event		Event Duration Time
	Deploys fuel, oxidizer, and He hoses and battery recharge cables	:13	
	Erection of solar array	:20	
	Erection of radiator	:30	
	Erection of antenna	:20	
27:30	Ingress to LCV shelter air lock and pressurize		:15
27:45	Doff pressure suits		:15
28:00	Personal maintenance (supper)		1:00
29:00	Housekeeping and maintenance of all systems		2:00
31:00	Setup internal experiment equipment		1:00
32:00	Sleep		8:00
40:00	Personal maintenance (breakfast)		1:00
41:00	Preparation for EVA		1:00
	Don and checkout pressure suits	:30	
	Don and checkout PLSS	:25	
	Enter air lock and dump pressure	:05	
42:00	EVA 7, scientist astronaut 1, surface temp 130 F		3:00
	Checks out LFV 1	:10	
	Flight out - 5 nm	:04	
	Conducts postlanding checkout	:05	
	Deploys launching mat	:10	
	Conducts exploration and experiments	1:37	
	Conducts preflight checkout	:05	
	Flight back - 5 nm	:04	
	Conducts postlanding checkout	:05	
	Moves scientific equipment from LFV 1 to LFV 2	:10	
	Refuels LFV 1, pressurizes He tanks, connects battery recharge cable, and deploys thermal blanket	:30	
	Scientist astronaut 2: Monitors and conducts internal experiments	3:00	
45:00	Ingress to LCV shelter airlock and pressurize		:15
45:15	Doff pressure suits		:15
45:30	Personal maintenance (lunch and rest)		1:00
46:30	Status conference with earth		1:00
47:30	Preparation for EVA (same as hour 41:00)		1:00
48:30	EVA 8, scientist astronaut 2, surface temp 150 F Same as EVA 7(42:00 hours) except range is assumed to be approximately 7 nmi		3:00
51:30	Ingress to LCV shelter air lock and pressurize		:15
51:45	Doff pressure suits		:15

Table 11. 14-Day Daylight Mission Time Line With Two LFV's (Cont)

Event Start Time	Event		Event Duration Time
52:00	Personal maintenance (supper)		1:00
53:00	Housekeeping and maintenance check		1:00
54:00	Conduct internal experiments		2:00
56:00	Sleep		8:00
64:00	Personal maintenance (breakfast)		1:00
65:00	Preparation for EVA (same as hour 41:00)		1:00
66:00	EVA 9, scientist astronaut 1, surface temp 170 F		3:00
	Same as EVA 7 (42:00 hours)		
69:00	Ingress to LCV shelter air lock and pressurize		:15
69:15	Doff pressure suits		:15
69:30	Personal maintenance (lunch and rest)		1:00
70:30	Status conference with earth		1:00
71:30	Preparation for EVA (same as hour 41:00)		1:00
72:30	EVA 10 and 11, surface temp 180 F		3:00
	Set up geophone array	1:00	
	Obtain seismic profiles with thumper	1:00	
	Dismount and assemble 100-300 foot drill	1:00	
75:30	Ingress to LCV shelter air lock and pressurize		:15
75:45	Doff pressure suits		:15
76:00	Personal maintenance (supper)		1:00
77:00	Housekeeping and maintenance check		1:00
78:00	Conduct internal experiments		2:00
80:00	Sleep		8:00
88:00	Personal maintenance (breakfast)		1:00
89:00	Preparation for EVA (same as hour 41:00)		1:00
90:00	EVA 12 and 13, surface temp 210 F		3:00
	Set up 100-300 foot drill	2:00	
	Commence drilling and check operation	1:00	
93:00	Ingress to LCV shelter air lock and pressurize		:15
93:15	Doff pressure suits		:15
93:30	Personal maintenance (lunch and rest)		1:00
94:30	Status conference with earth		1:30

Table 11. 14-Day Daylight Mission Time Line With Two LFV's (Cont)

Event Start Time	Event		Event Duration Time
96:00	Conduct internal experiments		4:00
100:00	Personal maintenance (supper)		1:00
101:00	Housekeeping and maintenance check		1:00
102:00	Discretionary time		2:00
104:00	Sleep		8:00
112:00	Personal maintenance		1:00
113:00	Preparation for EVA (same as hour 41:00)		1:00
114:00	EVA 14 and 15, surface temp 225 F		3:00
	Remove core samples and maintain drill	2:30	
	Check LFV's 1 and 2	:30	
117:00	Ingress to LCV shelter air lock and pressurize		:15
117:15	Doff pressure suits		:15
117:30	Personal maintenance (lunch and rest)		1:00
118:30	Status conference with earth		1:30
120:00	Day 6 - repeat of day 5 (96:00 to 120:00 hours)		24:00
144:00	Day 7 - repeat of day 5 (96:00 to 120:00 hours)		24:00
168:00	Day 8 - repeat of day 5 (96:00 to 120:00 hours)		24:00
192:00	Day 9 - repeat of day 5 (96:00 to 120:00 hours)		24:00
216:00	Day 10 - repeat of day 5 (96:00 to 120:00 hours)		24:00
240:00	Preparation for EVA (same as hour 41:00)		1:00
241:00	EVA 26 and 27, surface temp 200 F		3:00
	Remove drill	1:00	
	Log bore hold	1:00	
	Set up emplaced scientific package	1:00	
244:00	Ingress to LCV shelter air lock and pressurize		:15
244:15	Doff pressure suits		:15
244:30	Personal maintenance (supper)		1:00
245:30	Housekeeping and maintenance check		1:00
246:30	Discretionary time		1:30
248:00	Sleep		8:00
256:00	Personal maintenance (breakfast)		1:00

Table 11. 14-Day Daylight Mission Time Line With Two LFV's (Cont)

Event Start Time	Event		Event Duration Time
257:00	Preparation for EVA (same as hour 41:00)		1:00
258:00	EVA 28, scientist astronaut 1, surface temp 160 F Same as EVA 8 (48:30 hours). Upon return, refuels with balance of propellant in LCV (200 lbs)		3:00
261:00	Ingress to LCV shelter air lock and pressurize		:15
261:15	Doff pressure suits		:15
261:30	Personal maintenance (lunch and rest)		1:00
262:30	Status conference with earth		1:00
263:30	Preparation for EVA (same hour 41:00)		1:00
264:00	EVA 29, scientist astronaut 2, surface temp 150 F		3:00
	Checkout LFV 2	:10	
	Flight out - 5 nmi	:04	
	Conducts postlanding checkout	:05	
	Deploys launching mat	:10	
	Conducts exploration and experiments	1:37	
	Conducts preflight checkout	:05	
	Flight back - 5 nmi	:04	
	Conducts postlanding checkout	:05	
	Selects and loads samples to be returned to earth	:35	
	Connects battery recharger cable and deploys thermal blanket	:05	
267:30	Ingress to LCV shelter air lock and pressurize		:15
267:45	Doff pressure suits		:15
268:00	Personal maintenance (supper)		1:00
269:00	Housekeeping and maintenance check		1:00
270:00	Select internal experiments and data for return to earth		2:00
272:00	Sleep		8:00
280:00	Personal maintenance (breakfast)		1:00
281:00	Preparation of internal experiment samples for earth return		4:30
285:30	Personal maintenance (lunch and rest)		1:00
286:30	Status conference with earth		1:00
287:30	Preparation for EVA (same as hour 41:00)		1:00
288:30	EVA 30 and 31, surface temp 110 F		3:00
	Complete loading LFV's with samples to be returned to earth	:30	

Table 11. 14-Day Daylight Mission Time Line With Two LFV's (Cont)

Event Start Time	Event			Event Duration Time
	Scientist astronaut 1:		2:30	
	Checks out LFV 1	:10		
	Flies to ELM 0.5 nmi	:03		
	Conducts postlanding checkout	:05		
	Activates and checkout ELM systems	1:00		
	Transfers samples to ELM and store	1:07		
	Connects battery recharge cables and deploys thermal blanket	:05		
	Scientist astronaut 2:		2:30	
	Checks out LFV 2	:10		
	Makes LCV dormant	1:00		
	Flies to ELM, 0.5 nmi	:03		
	Conducts postlanding checkout	:05		
	Transfers samples to ELM and store	1:07		
	Connects battery recharge cables and deploys thermal blanket	:05		
291:30	Ingress to ELM and hook up ELM ECS			:10
291:40	Repressurize ELM and doff pressure suits			:20
292:00	Personal maintenance (supper)			1:00
293:00	Housekeeping and maintenance check			2:00
295:00	Complete stowing samples for earth return on board ELM			1:00
296:00	Sleep			8:00
304:00	Personal maintenance (breakfast)			1:00
305:00	Conduct test countdown and ascent stage launch			4:30
309:30	Personal maintenance (lunch and rest)			1:00
310:30	Status conference with earth			2:00
312:30	Preparation for EVA (same as hour 17:00)			1:00
313:30	EVA 32 and 33, surface temp 20 F			3:00
	Conduct final inspection of LM ascent stage		1:00	
	Inspect and adjust advanced ALSEP instrumentation		1:00	
	Miscellaneous tasks including possible medium-range flight to plant seismic charges		1:00	
316:30	Ingress to ELM and hook up ELM ECS			:10
316:40	Repressurize ELM and doff pressure suits			:20
317:00	Personal maintenance (supper)			1:00
318:00	Housekeeping and maintenance check			1:00
318:00	Review flight plan for rendezvous			1:00
320:00	Sleep			8:00
328:00	Personal maintenance (breakfast)			1:00
329:00	Conduct prelaunch countdown and checkout			3:00
332:00	Liftoff, surface temp -100 F			-

Table 12. LFV Rescue Mission Timeline

Assumptions/Constraints:

Emergency situation arose during prelaunch checkout prior to return flight on maximum-range (7 nmi) on EVA (5) of nominal three-day mission time line.

Rescued scientist astronaut is injured (sprained ankle and wrist).

Event Start Time	Event		Event Duration Time
27:15	Egress from ELM	:05	1:13
	Check out LFV 1	:10	
	Flight out - land approx 50 feet from injured crewman	:04	
	Deploy launching mat	:10	
	Deploy seat/supports	:05	
	Perform preflight checkout	:05	
	Transport injured scientist astronaut to LFV, position and secure him in seat	:10	
	Flight back	:04	
	Assist rescued scientist astronaut into ELM and hook up ELM ECS	:20	
28:28	Repressurize ELM or initiate prelaunch operations PLSS of rescued scientist astronaut in use for 3 hours, 28 minutes		

Table 13. Time Line of a Three-Day Dawn Mission With One LFV (No Rescue Capability)

Assumptions/Constraints:

- Lunar dawn landing with 10 degree sun angle at landing (-50 F) and 47 degree sun angle at liftoff (180 F)
- Lunar equatorial region mission (±15° lat)
- Three-day lunar surface stay time
- Two-man ELM with 1 LFV (no rescue) and an advanced ALSEP
- Eleven Hours of personal maintenance/rest per day
- 1000 pounds of propellant

Event Start Time	Lunar Stay Time Events		Event Duration Time
:00	ELM touchdown on lunar surface. Surface temp -50 F		-
:00	Checkout and activate ELM for lunar stay		2:00
	Postlanding checkout	:30	
	Launch simulation	1:30	
2:00	Science conference with earth		:30
2:30	Personal maintenance (lunch and rest)		1:00
3:30	Preparation for EVA		:30
	Don and checkout PLSS	:25	
	Dump cabin pressure and egress	:05	
4:00	EVA (1 and 2), surface temp -20 F		3:00
	ELM inspection	:20	
	Erection of solar array	:20	
	Erection of radiator	:30	
	Erection of antenna	:20	
	Dismount LFV	:10	
	Assemble LFV - mount scientific equip. on LFV	:05	
	Set up landing mat and aids 40 feet from ELM	:10	
	Move LFV 1 to mat 1	:05	
	Checkout LFV 1 (electronics/controls)	:10	
	Deploy fuel and oxidizer hoses and battery recharge cables	:10	
	Dismount and assemble advanced ALSEP	:40	
7:00	Ingress to ELM and hook up ELM ECS		:10
7:10	Repressurize ELM and doff pressure suits		:20
7:30	Personal maintenance		1:00
8:00	Housekeeping and maintenance check		1:00
9:30	Sleep		7:00
16:30	Personal maintenance (breakfast)		1:00
17:30	Preparation for EVA		1:00
	Don and check out pressure suits	:30	
	Don and check out PLSS	:25	
	Dump cabin pressure and egress	:05	
18:30	EVA (3 and 4), surface temp 45 F		3:00
	Scientist astronaut 1		
	Fuels LFV on mat and mount helium tank	:25	
	Checks out LFV	:10	

Table 13. Time Line of a Three-Day Dawn Mission With One LFV (No Rescue Capability) (Cont)

Event Start Time	Lunar Stay Time Events		Event Duration Time
	Flight out 0 -0.5 nmi - qual flt	:03	
	Postlanding checkout	:05	
	Deploys launching mat	:10	
	Local exploration	:30	
	Preflight checkout	:05	
	Flight back -0.5 nmi	:02	
	Postlanding checkout	:05	
	Monitors S/A 2 flight	:30	
	Completes setting up advanced ALSEP	:55	
	Scientist astronaut 2		
	Starts setting up advanced ALSEP	:60	
	Monitors S/A 1 flight	:30	
	LFV qualification flight same as above	:60	
	Refuels LFV - deploys thermal blanket, connects battery and recharge cables	:30	
21:30	Ingress to ELM and hook up ELM ECS		:10
21:40	Repressurize ELM and doff pressure suits		:20
22:00	Personal maintenance (lunch and rest)		1:00
23:00	Science conference with earth		1:00
24:00	Preparation for EVA (same as hour 17:30)		1:00
25:00	EVA 5, scientist astronaut 1, surface temp 85 F		3:00
	Replaces helium tanks	:10	
	Checks out LFV	:10	
	Flight out - 7 nmi	:04	
	Postlanding checkout	:05	
	Deploys launching mat	:10	
	Local exploration	1:37	
	Preflight checkout	:05	
	Flight back - 7 nmi	:04	
	Postlanding checkout	:05	
	Refuels LFV - deploys thermal blanket and connects battery and recharge cable	:30	
	Scientist astronaut 2 monitors	3:00	
28:00	Ingress to ELM and hook up ELM ECS		:10
28:10	Repressurize ELM and doff pressure suits		:20
28:30	Personal maintenance (supper)		1:00
29:30	Review results of flight with earth scientists		1:00
30:30	Housekeeping and maintenance check		1:00
31:30	Sleep		8:00
39:30	Personal maintenance (breakfast)		1:00
40:30	Preparation for EVA (same as hour 17:30)		1:00
41:30	EVA (6) scientist astronaut 2, surface temp 130 F		3:00
	Same as EVA (5)		
	Scientist astronaut 1 monitors		
44:30	Ingress to ELM and hook up ELM ECS		:10
44:40	Repressurize ELM and doff pressure suits		:20

Table 13. Time Line of a Three-Day Dawn Mission With One LFV (No Rescue Capability) (Cont)

Event Start Time	Lunar Stay Time Events	Event Duration Time
45:00	Personal maintenance (lunch and rest)	1:00
46:00	Science conference with earth	1:00
47:00	Preparation for EVA (same as hour 17:30)	1:00
48:00	EVA (7), scientist astronaut 1, surface temp 150 F	3:00
	Same as EVA (5) Scientist astronaut 3 monitors	
51:00	Ingress to ELM and hook up ELM ECS	:10
51:10	Repressurize ELM and doff pressure suits	:20
51:30	Personal maintenance (supper)	1:00
52:30	Housekeeping and maintenance check	1:00
53:30	Sleep	8:00
61:30	Personal maintenance (breakfast)	1:00
62:30	Preparation for final EVA's (same as hour 17:30)	1:00
63:30	EVA (8 and 9), surface temp 165 F	3:00
	Sample selection Sample storage Check ALSEP Check out ELM ascent stage	
66:30	Ingress to ELM and hook up ELM ECS	:10
66:40	Repressurize ELM	:05
66:45	Personal maintenance (lunch and rest)	1:00
67:45	Prelaunch countdown and check out	3:00
70:45	Liftoff, surface temp 175 F	-

Table 14. Three-Day Lunar Sunset Mission Time Line With One LFV

Assumptions/Constraints:

- Lunar pre-sunset landing with 20-degree sun angle at landing (80 F) and terminator 17 degrees below horizon at liftoff (-220 F)
- Three-day lunar surface stay time
- Two-man ELM with one LFV and an advanced ALSEP
- Eleven hours of personal maintenance/rest per man per day
- 1000 pounds of residual propellants available

Event Start Time	Lunar Stay Time Events		Event Duration Time
:00	ELM touchdown on lunar surface, surface temp 80 F		-
:00	Checkout and activation of ELM for lunar stay		2:00
	Postlanding checkout	:30	
	Launch simulation	1:30	
2:00	Science conference with earth		:30
2:30	Personal maintenance (lunch and rest)		1:00
3:30	Preparation for EVA		:30
	Don and checkout PLSS	:25	
	Dump cabin pressure and egress	:05	
4:00	EVA (1 and 2), surface temp 65 F		3:00
	ELM inspection	:20	
	Erection of solar array	:20	
	Erection of radiator	:30	
	Erection of antenna	:20	
	Dismount LFV	:10	
	Assemble LFV, mount scientific equip. on LFV	:05	
	Set up landing mats and aids 40 feet from ELM	:05	
	Checkout LFV (electronics/controls)	:10	
	Deploy fuel and oxidizer hoses and battery and recharge cable	:10	
	Dismount and assemble advanced ALSEP	:40	
7:00	Ingress to ELM and hook up ELM ECS		:10
7:10	Repressurize ELM and doff pressure suits		:20
7:30	Personal maintenance (supper)		1:00
8:30	Housekeeping and maintenance check		1:00
9:30	Sleep		7:00
16:30	Personal maintenance (breakfast)		1:00
17:30	Preparation for EVA		1:00
	Don and checkout pressure suits	:30	
	Don and checkout PLSS	:25	
	Dump cabin pressure and egress	:05	
18:30	EVA (3 and 4), surface temp 0 F		3:00
	Scientist astronaut 1		
	Fuels LFV on mat and mounts helium tank	:25	
	Checks out LFV	:10	
	Flight out - 0.5 nmi - qual flt	:03	
	Postlanding checkout	:05	

Table 14. Three-Day Lunar Sunset Mission Time Line With One LFV (Cont)

Event Start Time	Lunar Stay Time Events		Event Duration Time
	Deploys launching mat	:10	
	Local exploration	:30	
	Preflight checkout	:05	
	Flight back - 0.5 nmi	:02	
	Postlanding checkout	:05	
	Monitors S/A 2 flight	:30	
	Completes setting up advanced ALSEP	:55	
	Scientist astronaut 2		
	Starts setting up advanced ALSEP	:60	
	Monitors S/A 1 flight	:30	
	LFV qualification flight same as above	:60	
	Refuels LFV - deploys thermal blanket, connects battery and recharge cable	:30	
21:30	Ingress to ELM and hook up ELM ECS		:10
21:40	Repressurize ELM and doff pressure suits		:20
22:00	Personal maintenance (lunch and rest)		1:00
23:00	Preparation for EVA (same as hour 17:30)		1:00
24:00	EVA 5 scientist astronaut 1, surface temp -20 F		3:00
	Replaces helium tanks	:10	
	Checks out LFV	:10	
	Flight out - 7 nmi	:04	
	Postlanding checkout	:05	
	Deploy launching mat	:10	
	Local exploration	1:37	
	Preflight checkout	:05	
	Flight back - 7 nmi	:04	
	Postlanding checkout	:05	
	Refuels LFV - deploys thermal blanket	:30	
	Scientist astronaut 2 monitors	3:00	
27:00	Ingress to ELM and hook up ELM-ECS		:10
27:10	Repressurize ELM and doff pressure suits		:20
27:30	Personal maintenance (supper)		1:00
28:30	Housekeeping and maintenance check		1:00
29:30	Sleep		8:00
37:30	Personal maintenance (breakfast)		1:00
38:30	Preparation for EVA (same as hour 17:30)		1:00
39:30	SUNSET		-
39:30	EVA (6), scientist astronaut 2, surface temp -100 F		3:00
	Scientist astronaut 2:		
	Records and investigates sunset phenomena	1:00	
	Checks out LFV	:10	
	Multiple-stop flight (earthshine)	1:50	
	Scientist astronaut monitors		
42:30	Ingress to ELM and hook up ELM-ECS		
42:40	Repressurize ELM and doff pressure suits		:20

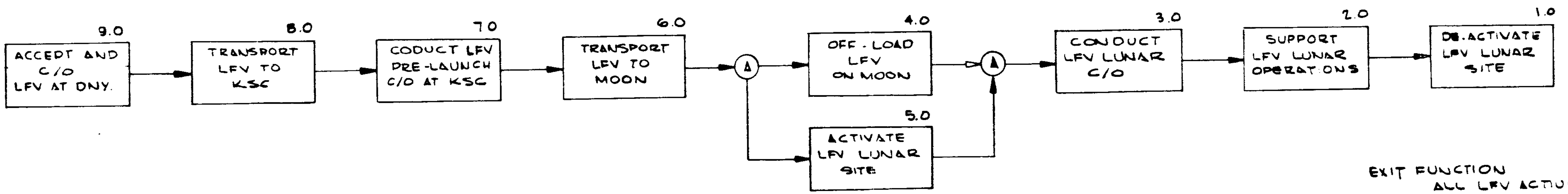
Table 14. Three-Day Lunar Sunset Mission Time Line With One LFV (Cont)

Event Start Time	Lunar Stay Time Events		Event Duration Time
43:00	Personal maintenance (lunch and rest)		1:00
44:00	Review scientific findings with earth scientists		2:00
46:00	Preparation for EVA (same as hour 17:30)		1:00
47:00	EVA (7), scientist astronaut 1, surface temp -170 F		3:00
	Scientist astronaut 2 monitors		
	Scientist astronaut 1		
	Checks out LFV	:10	
	Multiple-stop flight within walk-back range (earthshine)	2:50	
50:00	Ingress to ELM and hook up ELM ECS		:10
50:10	Repressurize ELM and doff pressure suits		:20
50:30	Personal maintenance (supper)		1:00
51:30	Review scientific findings with earth scientists		1:00
52:30	Housekeeping and maintenance check		1:00
53:30	Sleep		8:00
61:30	Personal maintenance (breakfast)		1:00
62:30	Preparation for final EVA's (same as hour 17:30)		1:00
63:30	EVA (8 and 9), surface temp -200 F		3:00
	Sample selection Sample storage Check ALSEP Checkout ELM ascent stage		
66:30	Ingress to ELM and hook up ELM ECS		:10
66:40	Repressurize ELM		:05
66:45	Personal maintenance (lunch and rest)		1:00
67:45	Prelaunch countdown and checkout		3:00
70:45	Liftoff, surface temp -220 F		-

APPENDIX C

FUNCTIONAL FLOW DIAGRAMS

ENTRY FUNCTION
LFV HAS BEEN COMPLETED BY NR'S MANUFACTURING AND IS TRANSFERRED TO TEST FOR ENGINEERING ACCEPTANCE.

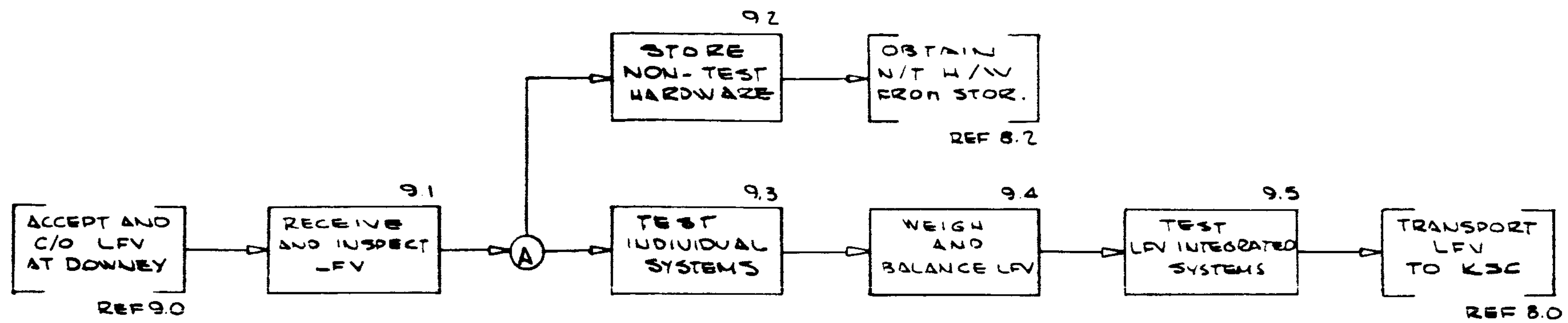


EXIT FUNCTION
ALL LFV ACTIVITIES HAVE BEEN COMPLETED - AREA CLEANED-UP AND ASTRO- RETURNED TO LEM.

Figure 43. Lunar Flying Vehicle Basic Flow - LFV Ground and Lunar Support Operations (Functional Flow Diagram 0.0)

ENTRY FUNCTION

MANUFACTURE OF LFV IS COMPLETED AND VEHICLE IS READY FOR ENGINEERING ACCEPTANCE TESTING.



EXIT FUNCTION

LFV HAS BEEN ACCEPTANCE TESTED AND IS READY FOR TRANSPORT TO KSC

Figure 44. Accept and Checkout LFV at Downey
(Functional Flow Diagram 9.0)

No.	Title	Tasks
9.0	ACCEPT & C/O LFV AT DOWNEY	
9.1	Receive and Inspect LFV	Remove LFV from transport vehicle.
		Unpackage and unpack LFV.
		Inspect for shipping damage.
		Move LFV to C/O station.
		Verify C/O station is ready for operation.
		Install LFV into stand.
		Verify completeness of documentation data package.
		Deploy landing gear.
		Deploy control console.
		Perform physical inspection.
9.2	Store Non-Test Hardware	Remove all loose equipment not required for Downey tests.
		Remove flight battery.
		Store all ancillary items not required for Downey tests.
		Store above items.
9.3	Test Individual Systems	Install GSE battery.
		Connect all necessary lines and cables for checkout and servicing of the LFV.
		Perform power-on tests.
		Perform He system leak tests.

No.	Title	Tasks
		Perform fuel system leak tests.
		Perform oxidizer system leak tests.
		Perform He system pressure tests.
		Perform fuel system pressure tests.
		Perform oxidizer system pressure tests.
		Perform gimbal actuator tests.
		Perform stability system tests.
		Perform instrumentation system tests.
		Perform throttle and throttle response tests.
		Shut down all systems.
		Disconnect all lines and cables.
		Remove GSE battery.
9.4	Weigh and Balance LFV	Install horizontal weight and balance adapters.
		Verify weight measuring system is ready for operation.
		Install flight battery and all other flight-required ancillary equipment.
		Activate and "null" the weight measuring system.
		Weigh LFV and record all values.
		Calculate horizontal c.g. location.

No.	Title	Tasks
		Relocate components and/or add weights if required to obtain proper c. g. location.
		Verify final weight and c. g. position; record values and component locations.
		Add weights to simulate flight loads (i. e., astronaut, fuel, He, oxidizer, cargo, etc.) for each planned flight configuration.
		Perform weight and c. g. operations for each flight configuration.
		Calculate cargo location changes, if required, to obtain proper horizontal location for each flight configuration.
		Verify and record weight, c. g. location, and cargo locations for each flight configuration.
		Remove all flight load simulation weights.
		Remove horizontal weight and balance adapters.
		Install vertical weight and balance adapters.
		Hoist LFV, rotate 90 degrees, and place on weight measuring system.
		Measure weights and calculate vertical c. g. location - record.
		Add weights to simulate flight loads (i. e., astronaut, fuel, He, oxidizer, cargo, etc.) for each planned flight configuration.
		Weigh, calculate c. g., and record data for each flight configuration.

No.	Title	Tasks
		Remove all flight load simulation weights.
		Hoist LFV, rotate 90 degrees, remove vertical weight and balance fixture, and place the LFV on the stand.
		Secure all weight measuring equipment.
		Remove flight battery and all flight-required ancillary equipment.
9.5	Test LFV Integrated Systems	Verify that station is ready for operation.
		Install GSE battery.
		Connect all lines and cables necessary for servicing, checkout, and simulation.
		Fill He, oxidizer, and fuel systems with GN_2.
		Conduct all operations to simulate an actual flight operation.
		De-service fuel, oxidizer, and helium systems.
		Incrementally fill the fuel tank with measured quantities of Freon TF and verify the fuel gauging system.
		Drain and purge the fuel system.
		Incrementally fill the oxidizer tank with measured quantities of Freon TF and verify the oxidizer gauging system.
		Drain and purge the oxidizer system.

No.	Title	Tasks
		Deactivate all systems.
		Remove all lines and cables.
		Remove GSE battery.
		Secure checkout station.

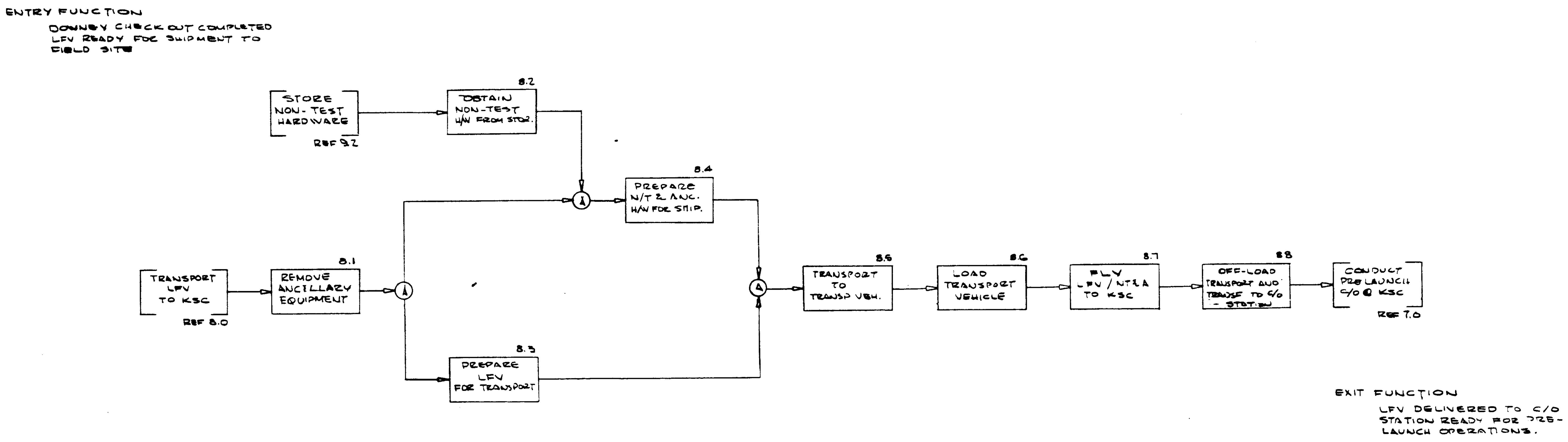


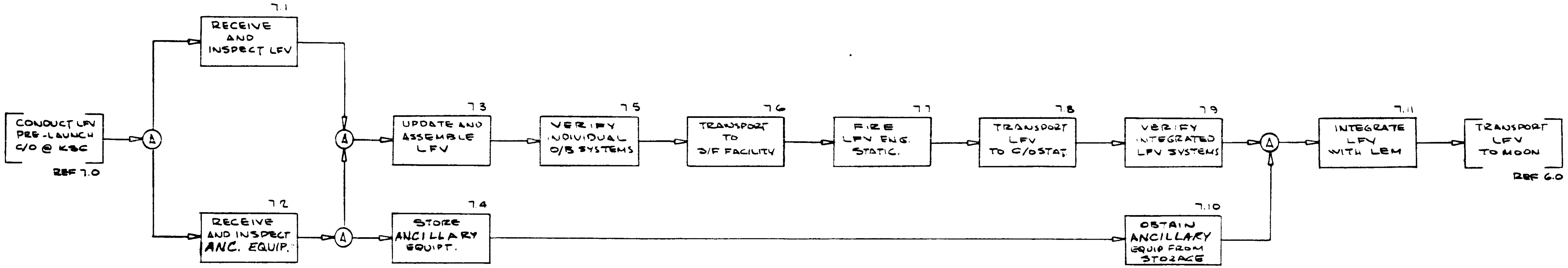
Figure 45. Transport LFV to KSC (Functional Flow Diagram 8.0)

No.	Title	Tasks
8.0	TRANSPORT LFV TO KSC	
8.1	Remove Ancillary Equipment	Remove all loose equipment and/or ancillary items.
		Perform physical inspection of each item.
		Transfer above items to packaging area.
8.2	Obtain Non-Test Hardware from Storage	Remove all non-test hardware from the storage area.
		Perform physical inspection of each item.
		Transfer all these items to the packaging area.
8.3	Prepare LFV for Transport	Perform physical inspection.
		Fold console into transport configuration.
		Fold legs into transport configuration.
		Remove LFV from stand and transfer to the packaging area.
		Package LFV for shipping.
8.4	Prepare Non-Test and Ancillary Hardware for Shipping	Package all non-test and ancillary hardware items for shipping.
8.5	Transport to Transport Vehicle	Load all packaged items onto vehicles and transport to airport.
8.6	Load Transport Vehicle	Unload all packages from vehicles and load onto airplane.

No.	Title	Tasks
		Secure all packages for flight.
8.7	Fly LFV and Non-Test and Ancillary Hardware to KSC	Transport all items to KSC by plane.
8.8	Offload, Transport, and Transfer to Checkout Station	Unload all packages from the airplane and load onto vehicles.
		Transport all packages to the receiving area.

ENTRY FUNCTION

LFV C/O AT DOWNEY COMPLETED. LFV TRANSPORTED TO KSC.



EXIT FUNCTION

LFV INTEGRATED WITH LEM AND READY FOR LAUNCH.

Figure 46. Conduct LFV Preflight Checkout at KSC
(Functional Flow Diagram 7.0)

No.	Title	Tasks
7.0	CONDUCT PRELAUNCH CHECKOUT AT KSC	
7.1	Receive and Inspect LFV	Remove LFV from transport vehicle.
		Unpackage and unpack LFV.
		Inspect for shipping damage.
		Perform physical inspection.
7.2	Receive and Inspect Ancillary Equipment	Remove all packages from transport vehicles.
		Unpackage and unpack all items.
		Inspect for shipping damage.
		Perform physical inspection of each item.
7.3	Update and Assemble LFV	Transfer LFV to C/O station.
		Verify C/O station is ready for operation.
		Install LFV into stand.
		Deploy landing gear.
		Deploy control console.
		Install all ancillary item required for KSC operations.
7.4	Store Ancillary Equipment	Store all ancillary items not required for KSC test and checkout operations.
7.5	Verify Individual On-Board Systems	Install GSE battery.

No.	Title	Tasks
		Connect all necessary lines and cables for checkout and servicing of the LFV.
		Perform power-on tests.
		Perform helium system leak tests.
		Perform fuel system leak tests.
		Perform oxidizer system leak tests.
		Perform helium system pressure tests.
		Perform fuel system pressure tests.
		Perform oxidizer system pressure tests.
		Perform gimbal actuator tests.
		Perform stability system tests.
		Perform instrumentation system tests.
		Perform throttle and throttle response tests.
		Shut down all systems.
		Disconnect all lines and cables.
7.6	Transport to Static Firing Facility	Hoist LFV from stand and place on transport vehicle.
		Transport LFV to the static firing facility.
		Remove LFV from transport vehicle.
7.7	Fire LFV Engines - Static	Verify station is ready for operation.
		Install LFV in stand.

No.	Title	Tasks
		Connect all lines and cables necessary to service and control LFV.
		Service helium system.
		Service fuel system.
		Service oxidizer system.
		Fire engines.
		Drain, flush, and purge the fuel system.
		Drain, flush, and purge the oxidizer system.
		De-service the helium system.
		Disconnect all lines and cables.
7.8	Transport LFV to Checkout Station	Remove LFV from stand and load on transport vehicle.
		Transport LFV to checkout station.
7.9	Verify Integrated LFV Systems	Verify checkout station is ready for operation.
		Install LFV in stand.
		Connect all necessary lines and cables for checkout, servicing, and/or simulation.
		Fill helium, fuel, and oxidizer systems with GN_2.
		Conduct all operations to simulate an actual flight operation.
		De-service fuel, oxidizer and helium systems.

No.	Title	Tasks
		Incrementally fill the fuel tank with measured quantities of Freon TF and verify the fuel gauging system.
		Drain and purge the fuel system.
		Incrementally fill the oxidizer tank with measured quantities of Freon TF and verify the oxidizer gauging system.
		Drain and purge the oxidizer system.
		Deactivate all systems.
		Remove all lines and cables.
		Remove GSE battery.
		Fold control console into transport configuration.
		Fold landing gear into transport configuration.
		Remove LFV from checkout stand and transfer to LM location.
7.10	Obtain Ancillary Equipment from Storage	Remove all ancillary equipment from storage.
		Perform physical inspection.
		Transfer to LM location.
7.11	Integrate LFV with LM	Install LFV on LM.
		Secure for flight.
		Install protective covers.
		Install all ancillary and accessory items on or in the LM and secure for flight.

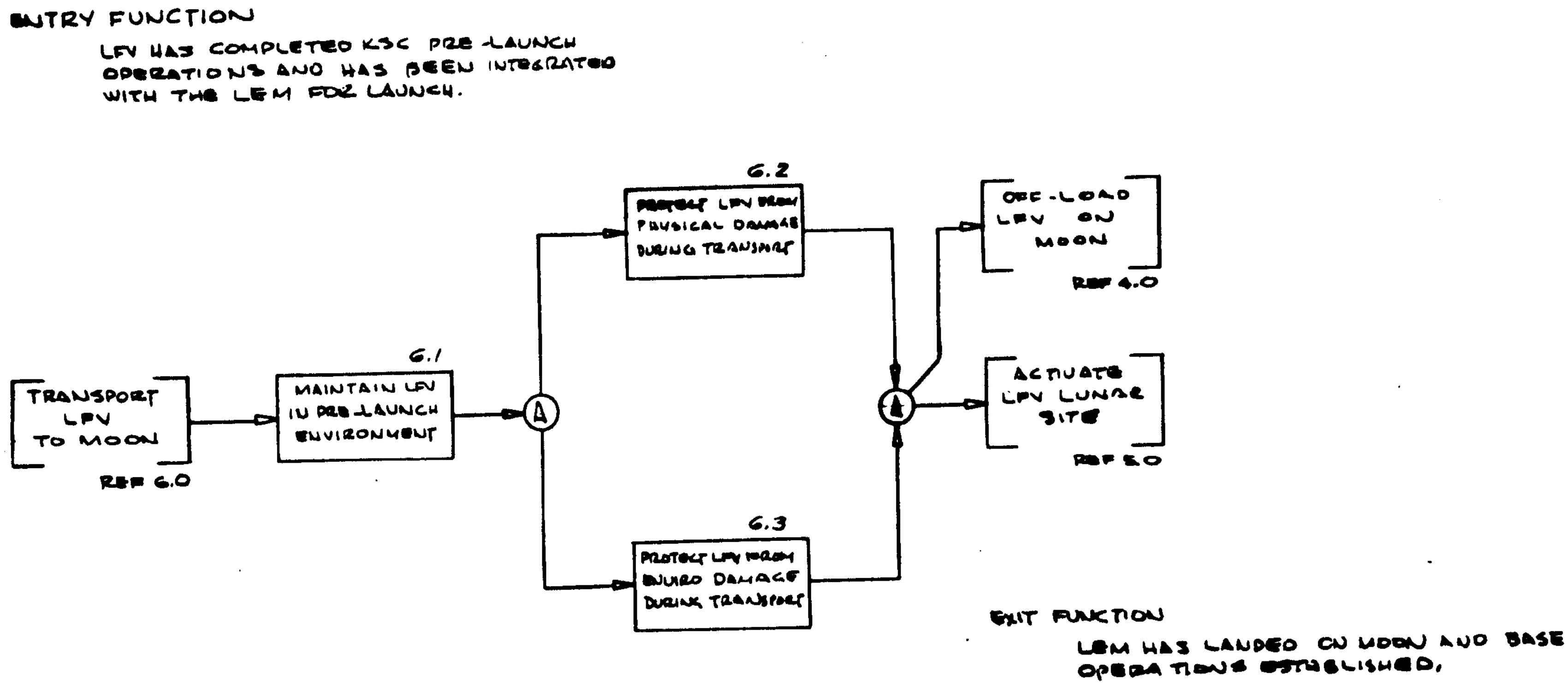
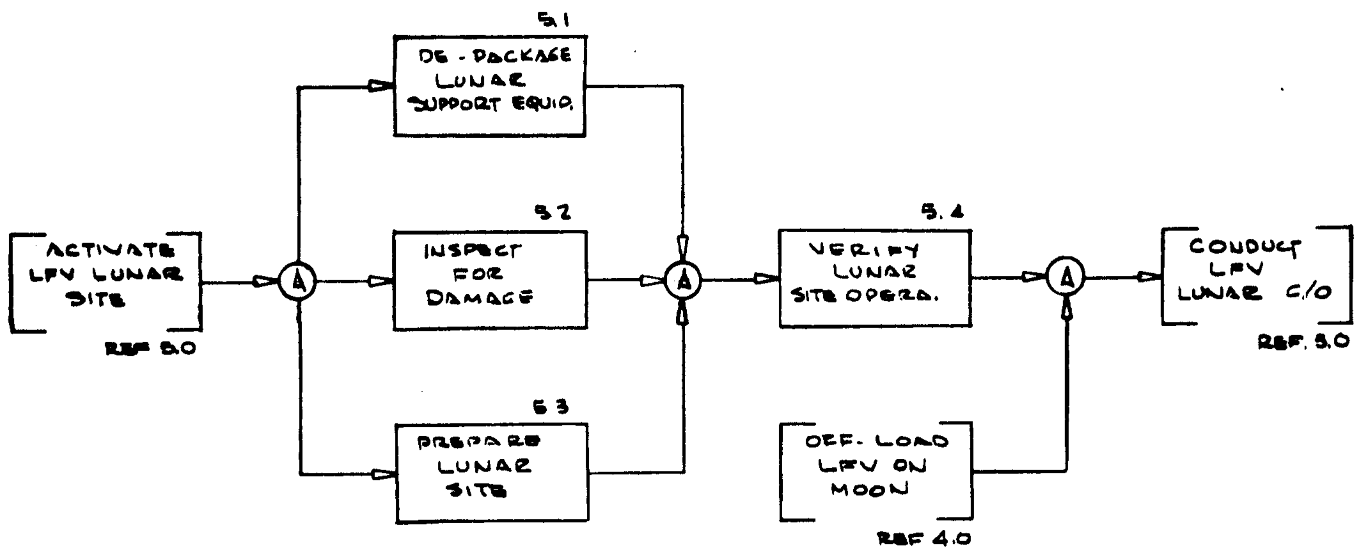


Figure 47. Transport LFV to Moon (Functional Flow Diagram 6.0)

No.	Title	Tasks
6.0	TRANSPORT LFV TO MOON	
6.1	Maintain LFV in Prelaunch Environment	Protect LFV from extreme environmental exposure during prelaunch operations. Protect LFV from physical damage during prelaunch operations.
6.2	Protect LFV From Physical Damage During Transport	Verify that all clamps, brackets, tie-downs, and other constraint devices are properly installed prior to launch.
6.3	Protect LFV From Environmental Damage During Transport	Verify that all protective covers and enclosures are properly installed and secured prior to launch.



NOTE: THIS FUNCTIONAL FLOW DIAGRAM IS INCLUDED TO DEFINE OPERATIONS REQUIRED TO SET UP LUNAR BASE AND WILL NOT IDENTIFY HARDWARE REQUIREMENTS BUT WILL AID IN ESTABLISHING OPERATIONAL PROCEDURES.

Figure 48. Activate LFV Lunar Site (Functional Flow Diagram 5.0)

No.	Title	Tasks
5.0	ACTIVATE LFV LUNAR SITE	
5.1	De-package Lunar Support Equipment	Remove all lunar support equipment items from LM.
		Unpackage and unpack all lunar support equipment items.
5.2	Inspect for Damage	Inspect all items for physical damage.
		Perform physical inspection of all items.
5.3	Prepare Lunar Site	Assemble (as required) all lunar support items.
		Select launch pad site.
		Deploy launch/landing pad.
		Erect/install landing aids.
5.4	Verify Lunar Site Is Operational	Perform physical inspection of completed site.

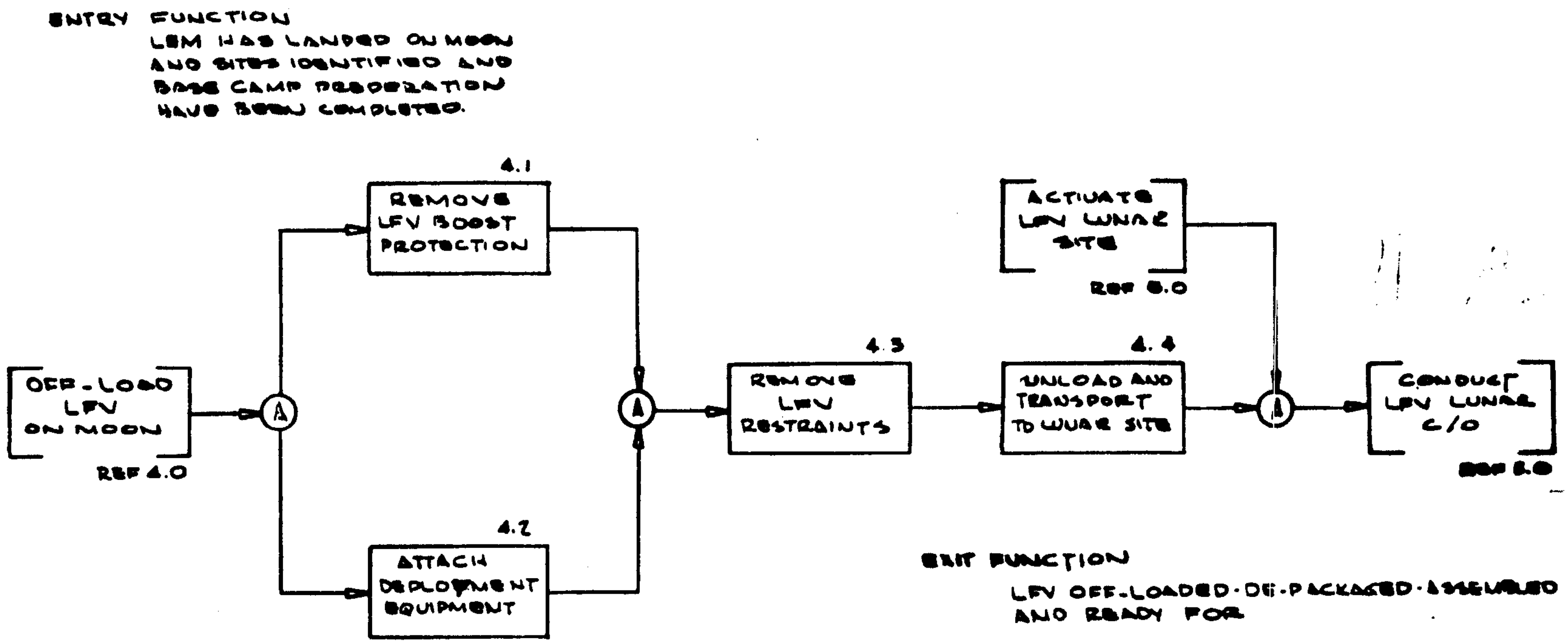


Figure 49. Off-Load LFV on Moon (Functional Flow Diagram 4.0)

No.	Title	Tasks
4.0	OFFLOAD LFV ON MOON	
4.1	Remove LFV Boost Protection	Unfasten and remove the protective covers and/or packing used to protect the LFV during the lunar trip.
4.2	Attach Deployment Equipment	Install operating handle on the deployment device. Attach the LFV frame to the deployment device.
4.3	Remove LFV Restraints	Unfasten and/or remove all restraints used to secure the LFV during the lunar trip. Position the LFV for unloading.
4.4	Unload and Transport to Lunar Site	Operate the deployment equipment to lower the LFV to the surface of the moon. Disconnect LFV from the deployment mechanism. Deploy LFV landing gear and stand the vehicle upright. Deploy control console. Transport the LFV to the launch area and place on launch pad (Refer to item 5.3).

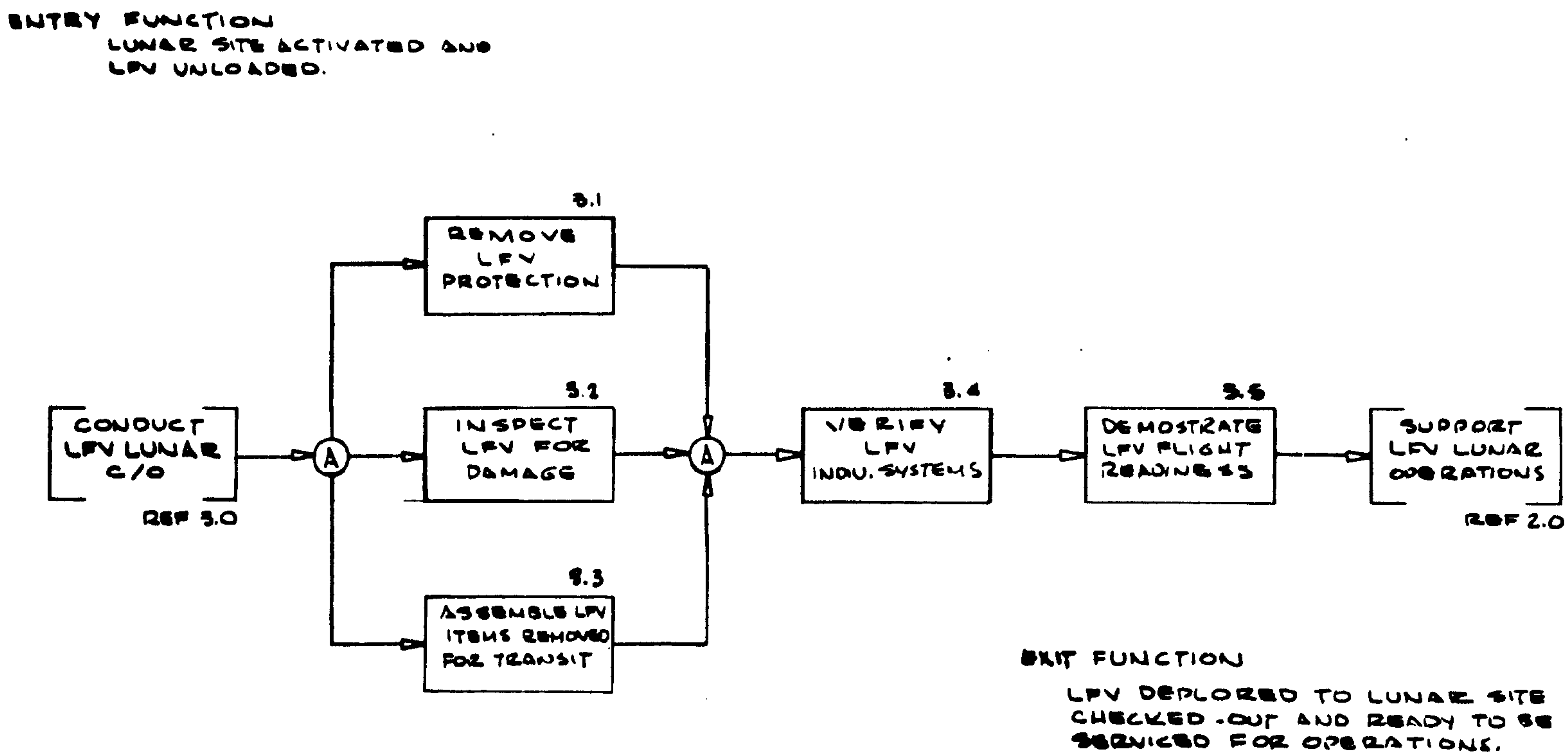


Figure 50. Conduct LFV Lunar Checkout (Functional Flow Diagram 3.0)

No.	Title	Tasks
3.0	CONDUCT LFV LUNAR CHECKOUT	
3.1	Remove LFV Protection	Remove all packing and packaging from LFV. Remove all environmental covers installed for flight to moon.
3.2	Inspect LFV for Damage	Inspect LFV for damaged parts or components. Perform physical inspection of LFV.
3.3	Assemble LFV Items Removed for Transit	Remove all ancillary items from LM. Unpack and unpackage all ancillary items. Inspect for shipping damage. Perform physical inspection. Install all ancillary items on the LFV. Inspect LFV for completeness.
3.4	Verify LFV Individual Systems	Install flight battery and helium tanks and fuel LFV (Refer to item 2.4). Perform power-on checks. Perform electrical and electronics checks. Perform throttle response and gimbal response checks.
3.5	Verify LFV Flight Readiness	Activate systems to just lift off pad, then secure engines.

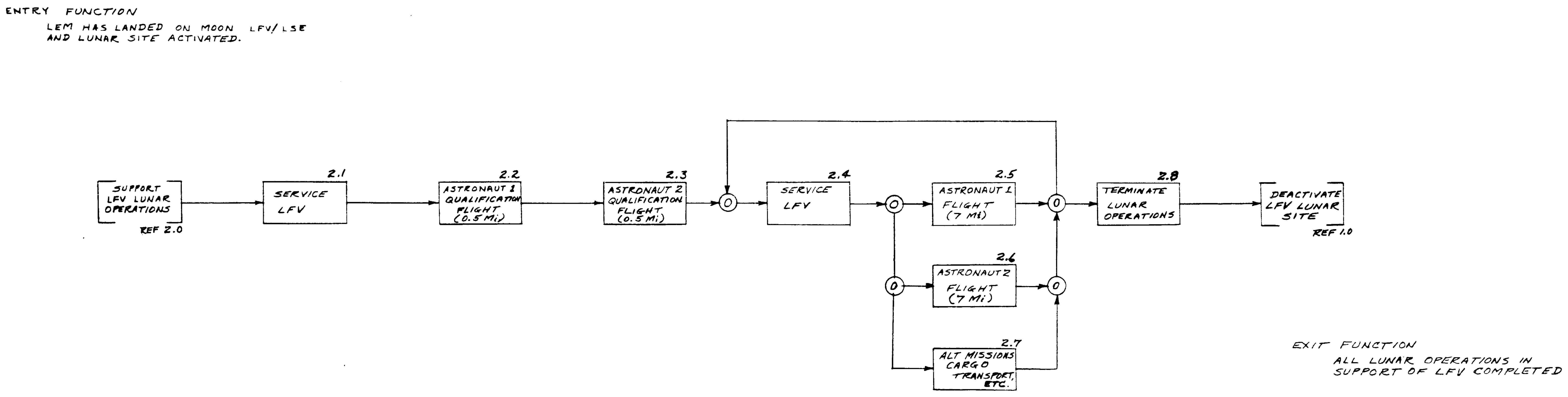


Figure 51. Support LFV Lunar Operations (Functional Flow Diagram 2.0)

No.	Title	Tasks
2.0	SUPPORT LFV LUNAR OPERATIONS	
2.1	Service LFV	Verify LM fuel and oxidizer valves are closed.
		Verify LFV helium, fuel, and oxidizer valves are closed.
		*Remove "empty" helium tanks from LFV.
		*Remove "expended" battery from LFV.
		Remove two full helium tanks and a flight battery from the LM, then install these items in the LFV.
		Connect fuel hose between the LM and the LFV.
		Install the fuel vent adapter on the LFV.
		Fill LFV fuel tank.
		Remove fuel hose and fuel vent adapter.
		Connect oxidizer vent adapter on the LFV.
		Install the oxidizer vent adaptor on the LFV.
		Fill the LFV oxidizer tank.
		Remove oxidizer hose and oxidizer vent adapter.
		Deactivate all LFV systems.
		*Deploy thermal blanket.

*Optional - Dependent upon condition of LFV and planned operations.

No.	Title	Tasks
2.2	Astronaut No. 1 Qualification Flight	*Remove thermal blanket. Activate LFV systems. Check out LFV electronics and control controls. Lift off and fly out 0.5 miles. Land and perform postflight checkout. Deploy launching mat. Conduct local exploration. Conduct preflight checkout. Lift off, return to base, and land on launch pad. Conduct postflight checkout. Deactivate all LFV systems. *Deploy thermal blanket.
2.3	Astronaut #2 Qualification	(same as 2.2)
2.4	Service LFV	(same as 2.1)
2.5	Astronaut #1 Flight	(same as 2.2, except range is seven miles)
2.6	Astronaut #2 Flight	(same as 2.2, except range is seven miles)
2.7	Alternate Missions - Cargo Transport, Etc.	(same as 2.2, except for loading and unloading of cargo as required by mission)

*Optional - Dependent upon condition of LFV and planned operations.

No.	Title	Task
2.8	Terminate Lunar Operations	Remove thermal blanket and load on LFV.
		Activate LFV systems.
		Check out electronics and controls.
		Lift off and fly to LFV storage area.
		Land and perform postflight checkout.
		Adjust helium pressure in fuel and oxidizer systems for long-term storage.
		Close all LFV shutoff valves.
		Deactivate all LFV systems.
		Remove flight battery and helium tanks.
		Deploy thermal blanket.
		Store battery and tanks in LM.

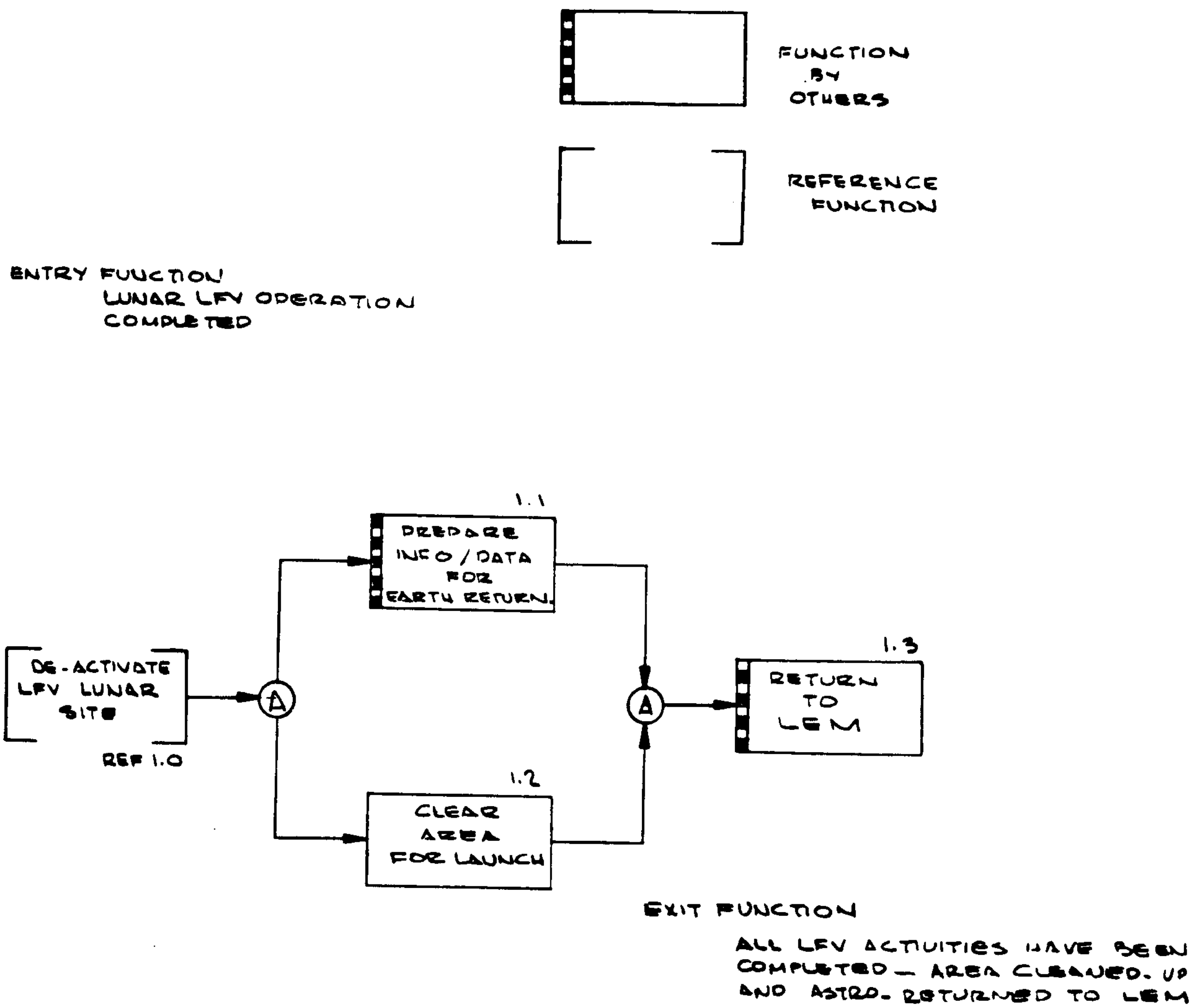


Figure 52. Deactivate LFV Lunar Site (Functional Flow Diagram 1.0)

No.	Title	Task
1.0	DEACTIVATE LFV LUNAR SITE	
1.1	Prepare Information Data for Earth Return	(for time-line reference only)
1.2	Clear Area for Launch	Pick up any item remaining in area and store in LM.
1.3	Return to LM	(for time-line reference only)